Proceedings of the Open University Geological Society

Volume 3 2017

Including lecture articles from the AGM 2016, the Exeter Symposium 2016, OUGS Members' field trip reports, the Annual Report for 2016, and the 2016 Moyra Eldridge Photographic Competition winning and highly commended photographs

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ISSN 2058-5209
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Proceedings of the OUGS 3 2017; published 2017; printed by Hobbs the Printers Ltd, Totton, Hampshire

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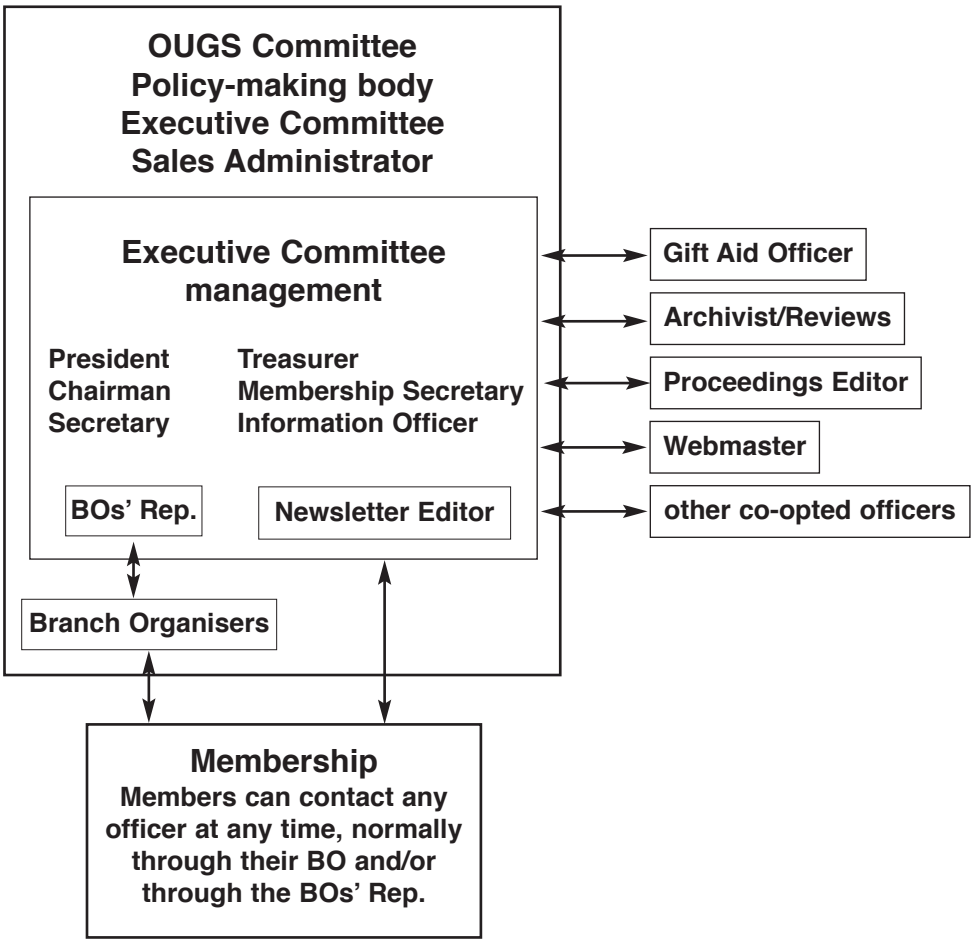

Editorial:

Dear readers,

This issue comprises articles from the speakers at our April 2016 AGM weekend in Scarborough; and at our July 2016 Symposium in Exeter, entitled, 'How the West was Made'; plus contributions from members and others.

First we are introduced again, by Will Watts, to our old friend William Smith, a driving force in the establishment of the Rotunda Museum, Scarborough, and to the largest theropod footprint found on the Yorkshire coast.

From the Geoff Brown Memorial Lecture 2016 we learn from Prof. Bill McGuire about the lasting effects of the Tambora volcanic eruption of 1815,

The lectures, and subsequent articles from the 2016 OUGS Symposium in Exeter range from analysis of how 'The Public' perceives geology, what people think is underground and the continuing discussions about issues such as fracking and other resource extraction, to a new view of what seem to be glacially created features on Dartmoor.

It was a pleasure to meet all the lecturers and to enjoy their co-operation in preparng articles for the OUGS Proceedings*; and, if readers will bear my indulgence, a special pleasure for me to meet and shake hands with one of my own geological-TV-star heroes, Prof. Iain Stewart.*

We learned a lot more about why the south-west of England is more than just a holiday and surfing destination!

I am sure that all OUGS Members who attend the symposia come away with feelings of satisfaction from the new knowledge imparted to us. For those who cannot attend, we strive diligently to help the lecturers prepare articles for us based on their lectures. Not only are these articles useful refreshers to Symposium delegates, but they also provide an opportunity for all OUGS Members to share the dissemination of geological knowledge focused on the particular theme of the Symposium in question.

It is unfortunate that some of our lecturers cannot find the time to write up their lectures into these short, but informative articles. But I wish to express my gratitude to those who do, and to our dedicated volunteer transcribers who work so hard to listen to and transcribe the lecture recordings to help the speakers in this endeavour. I assure members that, as Editor, I will continue to exercise the patience of all Symposium speakers to honour us with the not-really-so-onerous task of setting their research words onto paper for us.

I am disappointed and also apologetic that several of the Symposium lectures do not appear as articles. I'll say no more — editorial rants in public print are undignified — but given the tenor of Prof. Iain Stewart's article and implicit call for us scientists to do our utmost to spread the word ... Explanations are offered for each abstract.

Contributions from OUGS Members continue to come. These are most appreciated, and long may they continue.

In this issue we return to Andalucía in Spain for a second helping of the fascinating tectonics of the 'Mantle in the Mountains'. I had the privilege of taking part in the field trip, led by our outgoing President Dr Tom Argles, in 2015. As these Presidential trips are limited to 20 participants, it was inevitable that many who wished to go in 2015 had to be disappointed. So it was greatly appreciated that Dr Argles took up the mantle of leadership again to introduce a second group to this interesting geology. I should add that the wine, beer, food, people and music of this region of the world are worth going for as well! And, lastly, I would like to thank Linda Fowler and Jan Ashton-Jones for their careful organisation of this trip.

In addition to a description of the field geology of the Andalucían sierras, for you lab-rats among us, this time around we also have an analysis by Julian Overnell of some of the rocks and minerals. Two of his excellent thin-section photographs grace our Proceedings *cover this issue.*

And staying with Spain, the seemingly indefatigable Dr D. Woodcock — self-styled "continuing ES student" — gives us another fascinating short article, on the Miocene-Pliocene sediments of the Sorbas Basin of Almería in south-east Spain.

We all know how much we value our Society's relationship with the Open University itself. So it was a pleasant surprise to receive the offer of a contribution from one of its staff, Prof. Simon Kelley, to write us a review article chronicling the development of 'the virtual microscope'. Our members often swap stories about how, "when I took S236 ... and that microscope and box of thin-section slides arrived by courier..." (Your Editor vividly remembers a holiday in Galloway back in those heady days, when said microscope came with the family, so that he could rise at the crack of dawn to look at slides and keep up with his studies, alongside his daughter revising for her GCSEs, while certain other fmily members got to sleep in!)

We've come a long way in 'virtual' studies and in technological applications to help us in our 'distance learning'. Prof. Kelley provides us with an informative history of the geological microscope-in-a-box to the smart-phone-geology-app.

Speaking of our relationship with the OU, I would also like to draw readers' attention to the Annual Report for 2016*, separately paginated at the end of the* Proceedings*; in particular to the description from our new OUGS President, Dr Steve Blake, of the most recent developments and reorganisations of the sciences in the Open University structure (see* AR *page 8).*

And this year we have no fewer than 19 book reviews! For these we owe our thanks to the diligence of Archivist and Reviews Officer, Jane Michael, for her dedicated soliciting of publishers to get so many free review copies; and to our eager Members who read and reviewed them for us.

Finally, I want once again to express my gratitude to all those who help me produce this publication for you. Thank you to all you worthy transcribers who toil through our AGM and Symposium lecture recordings to provide transcriptions: this year to Jenny Parry, Isabel O'Brien, Anne Morton, Dick Millard, Averil Leaver, Marion Hastings, Lavinia Harvey, Michael Grover, Maggie Deytrikh, Lizzie Davenport, Rosemary Darby and Helen Coombs.

Thank you also to Linda Fowler, Don Cameron and Sue Vernon for their continued support and advice. A special thank-you to Sue Hughes who has become 'our proofreader' (last year's experience hasn't put her off!).

And lastly to my long-suffering wife, Anne, for listening to my complaints about the difficulties of page layout!

Now to end, just a little dig: how could you guys go to Granada and not *take in a flamenco show! You know who you are.* :-)

As always, I wish you happy reading.

— David M. Jones, OUGS Proceedings Editor

OUGS AGM 2016 Keynote Lecture

The varied geology of the Yorkshire coast

Will Watts

Director, Hidden Horizons

[Mr Watts wrote this article, based on a transcription of a recording of it, supplied at his request; as it was received only a few days before our printing deadline it has been edited by the OUGS Proceedings Editor.]

Introduction

The Yorkshire coast has both some stunning geology and an illustrious history of geological discovery. This overview can only touch upon these elements, as well as illustrate some of the more recent developments, and finally indulge my own links to this part of the world. I was born in Scarborough and raised in the middle of the North York Moors National Park, the stunning heather moorland to the North of Scarborough. I have made quite a bit of my career in Scarborough, for 12 years with Scarborough Museums — notably at the Rotunda Museum; and since 2013 running my own company, called 'Hidden Horizons'. The talk that I gave to the OUGS AGM in Scarborough on 15 April 2016 was a light-hearted, whistle-stop tour of the Yorkshire coast, its geology, the history of geological discovery in the area and some more recent developments, all wrapped up in my own life in and around Scarborough — thus a personal viewpoint (Figs 1 and 2, *overleaf*).

The geological cross section in Figure 3 *(overleaf)* is a good place to start. Produced by John Philips for his book *The Geology of the Yorkshire Coast* in 1829, it shows the coastline from Filey in the south all the way up through Scarborough to Cloughton Wyke, about five miles north of Scarbrough. It not only shows the variety of the geology we have to offer on the coast, but also neatly demonstrates how the area is linked to the early days of the science. What follows is a very brief 'virtual field trip' along the Yorkshire coast in a selection of images, and a focus on the history and redevelopment of the Rotunda Museum, including some relatively recent discoveries featured in it.

The Rotunda Musuem

William Smith himself, the 'Father of English Geology', played an important part in the building of the Rotunda Museum (Fig. 4, *page 3*). To understand why the museum was built in 1829 and

Figure 1 Robin Hood's Bay with the sweeping view of its lower lias fossiliferous mudstone and shale cliffs.

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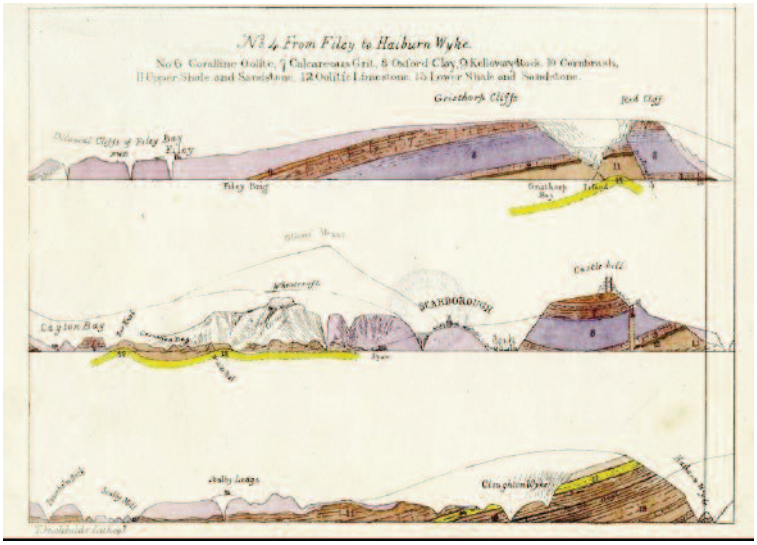
ISSN 2058-5209

Figure 2 Chalk cliff and stacks at Flamborough Head.

Smith's role in this work we first need to look at the formation of the Scarborough Philosophical Society (SPS) and at Thomas Hinderwell, who was an antiquarian interested in 'everything' (Fig. 5, *opposite*). Hinderwell collected specimens of geology, natural history, archaeology and what we would today call 'social history'; and he wrote a series of books about the history of Scarborough, which are still useful reference books today.

Figure 3 Section drawings from John Phillips' Geology of the Yorkshire Coast *(1829).*



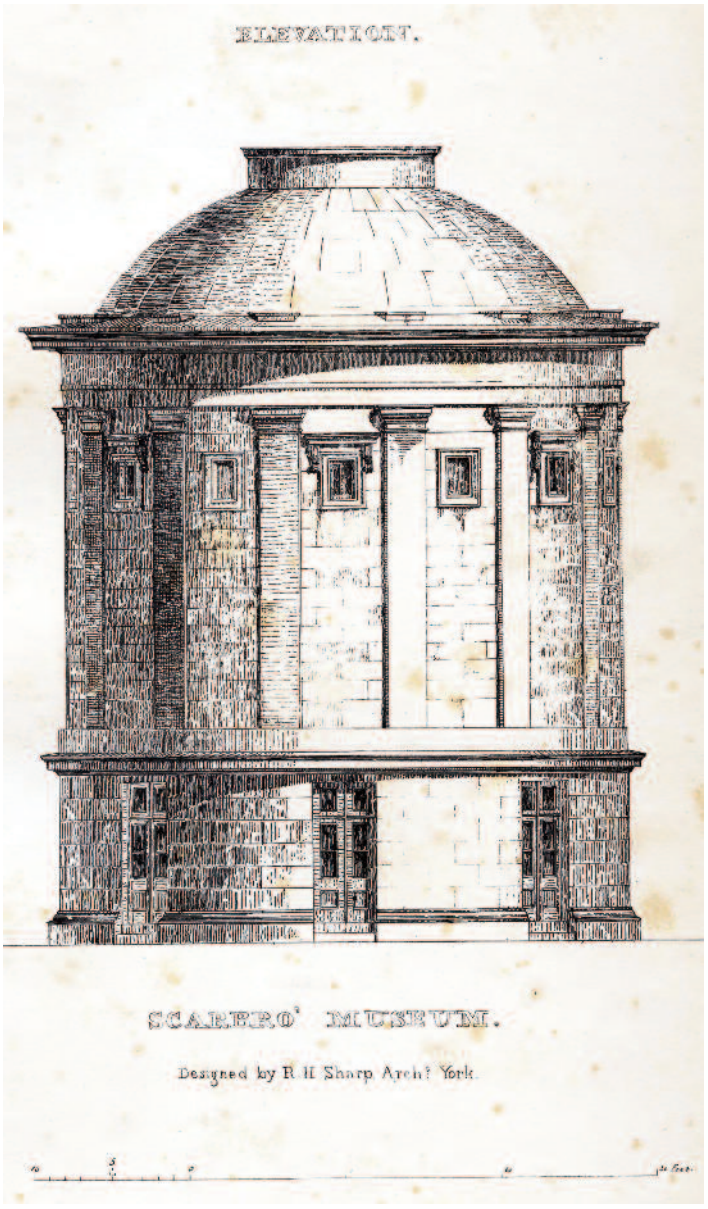
He was active in the last three decades of the 18th century, and it is his collection that became the starting point for the Rotunda Museum and the SPS. However, the early 19th century SPS had a march stolen on them by both York and Whitby. The Whitby Literary and Philosophical Society had built their museum earlier, and the Yorkshire Society was older still, so the Scarborough Philosophical Society was playing catch up, led in particular by local MP Sir John Johnstone, who became President, and by Thomas Hinderwell, along with a group of Scarborough residents; and they were joined by William Smith, who had come out of debtors' prison, had moved up to Scarborough, and had become land agent to Sir John Johnstone.

Before the opening of the Rotunda Museum in 1829 Smith had given series of lectures in the Scarborough town hall, ably assisted by his nephew, John Phillips. I would argue that in some ways Phillips was an even more important geologist than Smith, but they were both already well known in the town and they were active in the region. Smith's and Phillips' lectures in some ways gave the local collectors a framework for collecting: instead of collecting specimens just because they looked 'pretty' – of which we are all guilty – they started to collect with more purpose. And they needed somewhere to display that framework. Smith was approached and asked, firstly, if he would be site foreman, to which he agreed; and secondly, if he were to design the museum, what shape would it be? His 'immortal' reply was that he wanted a space where he could take in at a single glance all of the observations he had made on the coastline — and for some reason, that

Figure 4 William Smith, "The Father of English Geology".

Figure 5 Thomas Hinderwell, Scarborough antiquarian.

Figure 6 Elevation drawing of the Rotunda Museum.



vision became a circle (Fig. 6). However, thinking about it, a circle does not work ideally, because there is always something behind you! Nephew John Phillips was also an important part of the equation. He went on to become the first Keeper of Geology at the Yorkshire Museum in York.

The building stone for both of these museums came from the same quarry. The whole project seems to have been 'incestuous', for SPS President Sir John Johnstone's sister was married to William Veronon Harcourt, the first President of the York Society. So the whole affair was a 'done deal'. Using the same building stone turns out to be an interesting exercise. If you compare the state of the stone at the Yorkshire Museum with that of the Rotunda Museum you will immediately see the phenomenal erosion of the latter — the effect of the coastal erosion. Although the buildings were built within five years of each other, the Yorkshire Museum looks as if it was built perhaps 50 years later!

The main catalyst for the Yorkshire Museum was Kirkdale Cave, very close to where I was brought up as a child — I actually remember crawling through the cave as a lad before, as a geologist, I knew anything about its importance. As we have seen, Phillips, produced some fantastic geological work on the Yorkshire coast. Some of his cross sections were reproduced as displays in the Rotunda (Fig. 7, *overleaf*).

One of William Smith's specifications for the Rotunda was that he wanted was sloping shelves, in order to display the fossils in the same order in which they are found in the ground — a beautifully simple way of displaying material stratigraphically; and by using sloping shelves you can get display more (Fig. 8, *page 5*). Interestingly, most of the rocks on the Yorkshire coast dip north to south stratigraphically (right to left, as it were), but when the shelves were put into the museum, you can see in outlines of them on images from the 1950s that they sloped from left to right — the opposite way to the geology on the cross section.

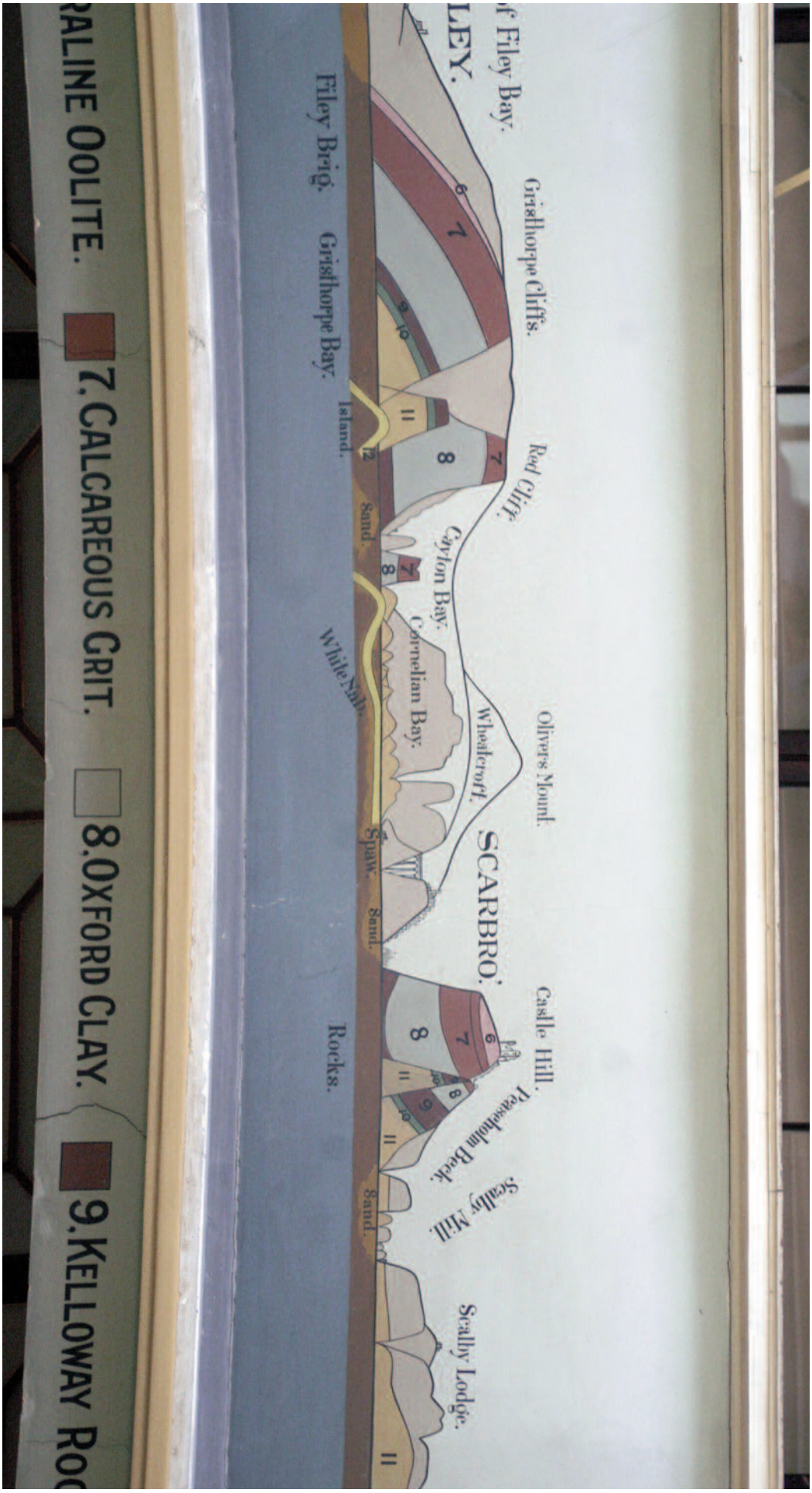


Figure 7 The 1901/2008 painted cross section of the Yorkshire coastline in the Rotunda Museum.

Someone got the project management wrong! Once the museum building had been completed, Smith contracted a carpenter to put in sloping shelving, but apparently neglected to tell him which way they should slope. Painters were next contracted to paint the cross section, and this original cross section had to be painted 'the other way around' because it had to follow the slope of the shelves. The section painting you see today is a repainting in 1901, but in places you can see traces of the original painting beneath. The repainted section shows the Yorkshire coast as if you are on a boat looking back at the cliffs. However, the original section paintings must have been confusing, as they would have appeared as a mirror image of the coastal cliffs! Cross sections are one of the simplest tools we have to explain geology to the general public, but when it is the wrong way round it takes some careful thinking to understand it.

When we redeveloped the Rotunda displays in 2008 we faced a dilemma: do we go back to the original cross section, or do we keep it as it was 'corrected' in 1901? We decided to keep the section painting the right way round (sloping right to left, as in Fig. 5) and instead of putting the sloping shelves back in we painted sloping bands of colour, which as geologists we all recognise. Thus the stratigraphy in the background matches the key that was always there.

The first keeper of the Rotunda Museum was John Williamson, who is probably one of my favourite early geologists; but he was not just a geology curator, for he also did all the weather records; he was sent to Manchester to learn how to do taxidermy; and he returned with a great quantity of glass eyes, such a quantity that the museum still has a large box of glass eyes that were never used. His son, William Crawford Williamson, who was the first curator at the Manchester Musuem, was initially famous for some early archaeology — the excavation and lifting of 'Gristhorpe Man', a Bronze Age burial displayed in the Rotunda (Fig. 9, *overleaf*). Williamson, at age 17, wrote the first scientific monograph on Gristhorp Man. The skeleton is 5ft10in, and the burial is the most complete Bronze Age log burial in the UK. The skeleton is so complete that in 2006 when we emptied the museum for the redevelopment work, we sent it to Bradford University (a centre for scientific investigative applications in archaeology) to prove that he was not a fake. For there had always been rumours that the skeleton was a composite of more than one individual, and that it was not in fact even Bronze Age in date. Bradford scientists' investigations showed that Gristhorpe Man is, in fact, Bronze Age in date, and that he is one individual; also that he was tall for a man in 4000 BC.

Yorkshire coast continuing research

The Yorkshire coastline is still an area of important, active research. There is always the suggestion that it has 'all been done', that we have it all sorted out and that the papers have been published. But it does not always happen like that. I started at Scarborough Museums in early 2002 and almost straight away Nigel Armstrong who is a very keen, very proficient, good and responsible amateur collector discovered some bones at the bottom of the cliff at Speeton, including a centrum from the vertebra of a plesiosaur. Plesiosaurs have long necks, barrel bodies

Figure 8 The Rotunda Museum gallery.

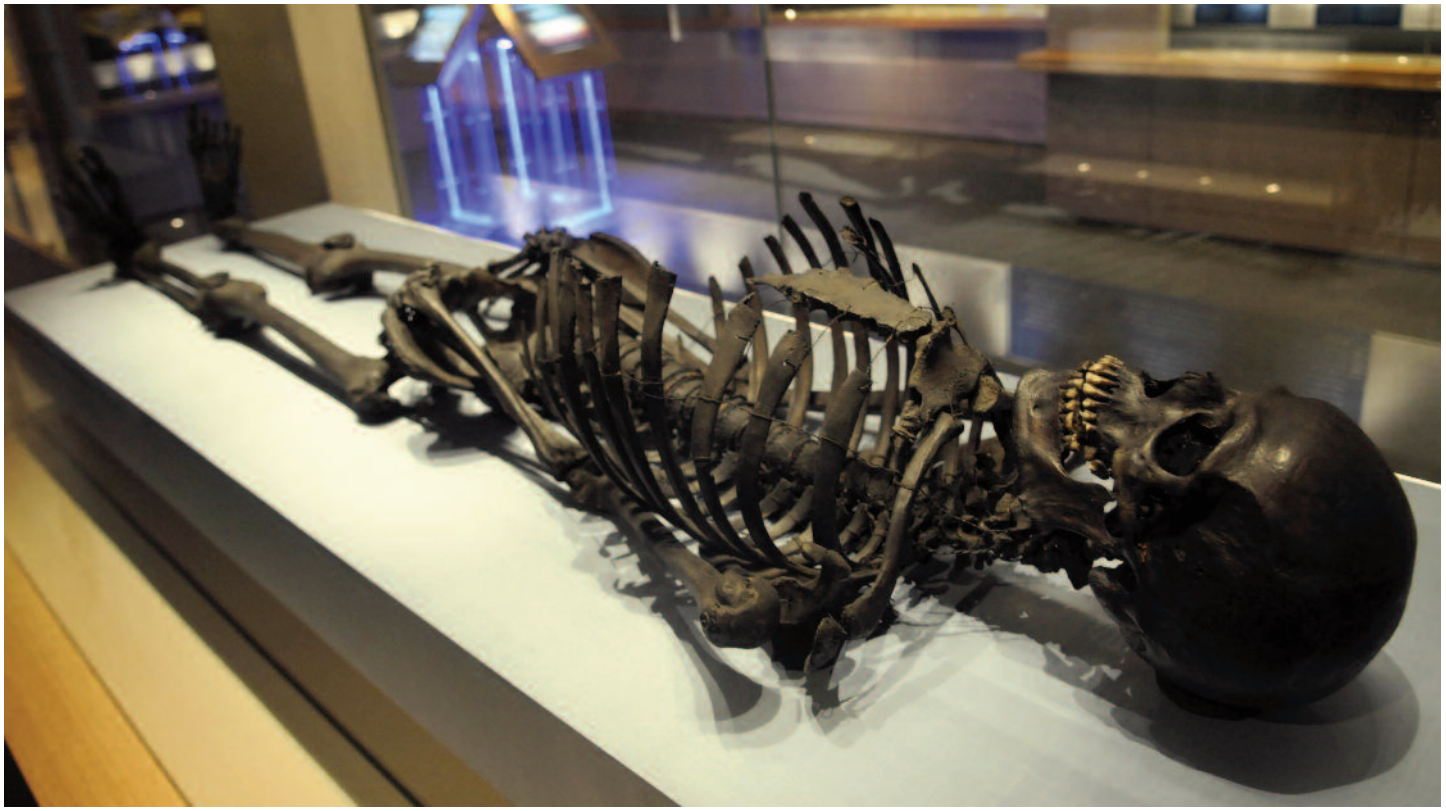


Figure 9 Rotunda Museum display of the 'Gristhorpe Man' Bronze Age burial skeleton.

and four flippers. Nigel found one of these and then a bit higher in the cliff he found another one and then a third. At this point he thought something might be going on, so he did the right thing — he stopped. He was more than capable of excavating huge amounts of this find, and he is experienced enough to have done a good job of it, but he also had the good sense to stop and make a few telephone calls to fellow geologists and palaeontologists.

We put together a team of people in October 2002 and spent 10 days excavating this plesiosaur, 10 days of difficult work in the Speeton clay, which is awful in the wet (Fig. 10, *opposite*). The original plan was to excavate as normal, exposing the bones; but we quickly realised that there was more bone than clay in some parts. It was as if this creature had been put in a hessian sack, tapped on the head and dumped — ending up as a big heap. There was very little articulation, very few bones in their original positions, and there had been a lot of movement of the Speeton Clay.

The Speeton Clay is wedged between the Cretaceous Chalk and the Kimmeridge Clay. The Kimmeridge Clay, like the Speeton clay also quite soft, sits above the Upper Jurassic limestones. So there has been much tectonic activity in the area and it has affected the Speeton Clay. In the end we decided to prepare a good old-fashioned plaster jacket, wrap the plesiosaur bones in hessian strips and plaster, borrow some National Trust Land Rovers and drag this stabilised 'package' down the cliff. Mike Marshall, one of the best preparators on the coastline, then spent three years gluing the plesiosaur back together. When I left the Rotunda Museum in 2010 there were still 17 boxes of fragmented ribs still to be stuck together. It was mind-numbing work and needed somebody with greater patience than I had.

Eventually, however, we were able to display the rebuilt plesiosaur, as shown in Figure 11 *(opposite)*. It is a fantastic beast, but unfortunately we never found the head — the sad fact is that as we excavated, following the vertebrae up the neck, we reached the top of the cliff of Speeton Clay, getting closer to the junction of the Speeton Clay and the boulder clay and glacial till. If the plesiosaur's head had survived being scavenged or eaten on the seabed, a later ice sheet must have removed it.

Another example of recent Yorkshire coast research has been the discovery of Middle Jurassic dinosaur footprints. Mike Romano and Martin Whyte of Sheffield University (Fig. 12)

Figure 12 Martin Whyte being interviewed about the new Rotunda Museum dinosaur displays.

Figure 10 The Speeton plesiosaur being excavated.

Figure 11 Rotunda Museum display of the Speeton plesiosaur.

started serious exploration for dinosaur footprints along the Yorkshire coast in the 1980s. Before their work, everyone assumed that there was only one location, a single horizon, and you occasionally found dinosaur footprints in it. *[See Romano, M. 2009 'Dinosaur footprints on the Yorkshire coast'*. OUGSJ ***30*** *(2), 17–25 —Ed.]*

We have now found trace fossils of nearly 30 dinosaur and other vertebrate, representing all the big sauropods, and possibly stegosaurs. These are dinosaurs with three-toed feet, big herbivores (iguanodontids), and massive carnivores right down to the smallest ones (Fig. 13). We have traces of dinosaur swimming, traces of fish, turtles, crocodiles and, more recently, feeding traces of pterosaurs. The story of dinosaurs along the Yorkshire coast is being filled in, creating a fantastic story.

One of the most important recent footprint finds is of the largest carnivorous therapod footprint ever found on the Yorkshire coast. From the tip of its claw to the back of its heel it measures 630mm (or just over 2ft). Extrapolating, this foot size means a leg length of *c*. 2.4m. The only other big predator that we know from the Middle Jurassic rocks of this age is the megalosaur first described by William Buckland from Oxfordshire, As this Yorkshire carnivorous therapod is broadly of the same age, it is thought also to be a megalosaur-type dinosaur.

This megalosaur-theropod footprint was found just north of Scarborough at Burniston Bay by another amateur collector, John Hudson. As with Nigel Armstrong's plesiosaur find described above, we followed all the usual procedures: we recorded it, photographed it, took plaster casts of it, and then decided to try and recover it — it only weighs half a ton! First I rang the Coast Guard, but they had just taken the heavy winches off their Sea King helicopters, so they could not lift it. We tried all the military branches that might be interested in some sort of daft exercise, but none of them were up for it. Finally, John Hudson himself, who at the time was a keen diver, approached sub-aqua clubs. Members of the Scarborough Sub-Aqua Club, who had built a raft that they tested at the annual Boxing Day Raft race in the harbour, rose to the challenge. A few days later we managed to get the rock with the footprint into a box, transport it down the beach (Fig. 14), and then strap it to the raft with its four 45-gallon oil drums in the North Sea and tow it back to Scarborough harbour (Figs 15–16, *opposite*). It was lifted out, allowed to dry and is now on display at the Rotunda Museum (Fig 17, *opposite*).

Figure 13 Theropod footprint.

Figure 14 Carrying the boxed Burston theropod footprint down the beach to the raft.

This brief look at the fantastic geoheritage of the Yorkshire coastline, is not meant to be anything more than a teaser to encourage people to get out and explore the Yorkshire coast themselves.

Figure 15 Floating the half-ton theropod fossil on a raft with 45-gallon oil drums.

Figure 16 Towing the theropod fossil into Scarborough harbour.

Figure 17 The Burston Bay megalosaur-theropod footprint.

Book review

Kear, B. P., Lingren, J. Hurum, J. H., Milan, J., and Vajda, V. 2016 *Mesozoic Biotas of Scandinavia and its Arctic Territories*. London: The Geological Society (ISBN 978-1-86239-748-4; hardback, 327pp; £100)

This book is an absorbing collection of 18 scientific papers that deals comprehensively with the Mesozoic marine and terrestrial fossil record for this geographical area. This is not a book for the layman and requires a good knowledge of palaeontological and plant terminology, as well as of geology.

The introduction gives an overview of the subject that certainly whets the appetite. The first paper deals with the foundation of Mesozoic palaeontology in Sweden in the late 19th and early 20th centuries. Papers 2–6 describe various Triassic Biotas from Svalbard and East Greenland, and contain a number of fascinating insights. Paper 6 describes how isotope analysis of temnospondyl (amphibian) bones infers that they may have undergone migrations from marine to freshwater environments, as salmon do today. The papers vividly describe how East Greenland would have been located 40° north in a semi-arid lacustrine environment that became wetter through time; while Svalbard would have been located roughly 55–60° north in a low-lying, peat forming deltaic environment.

Papers 7–9 deal with the Jurassic, which is concentrated in southern Sweden and Svalbard. Paper 7 states how volcanic activity on a failed rift system preserved a comprehensive fossil record of whole plant communities in what is known as a Lagerstätte. A fern spore spike at the junction of the Triassic and Jurassic provides evidence of the Triassic mass extinction. Paper 9 relates to a marine Lagerstätte in Spitsbergen, where the remains of plesiosaurs, pliosaurs and ichthyosaurs were deposited and preserved in anoxic conditions on the seabed. It explains how oceanic currents and the fact that some of these animals may have floated while decaying may have had a bearing on their subsequent taphonomy.

The remaining eight papers deal with the Cretaceous, and again most of the fossils come from southern Sweden. Paper 10 is an exception and describes how Svalbard was part of the American landmass in the early Cretaceous; and provides new evidence that Iguanadontid dinosaurs were found in the Americas, where they were hitherto unknown. Paper 11 describes how plant remains deposited in a near shore environment enabled a detailed inference to be made of the plant communities of southern Sweden. Also found are a small number of dinosaur bones from animals that had been washed out to sea, the most important being the remains of a small horned dinosaur. Its presence here indicates that horned dinosaurs had reached Europe by at least 87 Mya. Until recently it was believed that these dinosaurs were restricted to Asia and North America.

I thoroughly enjoyed reviewing this book and the comprehensive references attached to each papers facilitate further research. I hope that the selected subject matter examples here given encourage people to purchase this book.

— Mark A. Barrett, BSc Hons Natural Sciences (Open)

Book review

Scriven, Samuel 2016 *Fossils of the Jurassic Coast*. East Lulworth: The Jurassic Coast Trust (ISBN 978-0-99311-071-9; paperback, vi + 220pp; £14.95; available from bookshops and from http://jurassiccoast.org/product/6264/)

I have recently bought a copy of this book by Samuel Scriven, who has led many of our Wessex OUGS annual fossiling trips on the Dorset coast. It is a difficult task to write a book on a subject that not only appeals to the layman with no prior knowledge of the topic but also to those of us who have a deeper interest. Scriven has managed to do this admirably.

The book is divided into four parts. Parts One and Two deal briefly with an overview of the Jurassic coast and how fossils are formed, plus the history of the Earth prior to the Mesozoic. The bulk of the book is contained in Part Three, which takes you on a journey through time, starting at the western edge of the Jurassic Coast in the Triassic Budleigh Salterton Pebble Beds and finishing at the eastern edge in the Chalk Group at Old Harry Rocks.

There are some quite stunning photographs and illustrations of fossils throughout, some of which were provided by our OUGS group member Alan Holiday. As we travel through time, the various ecosystems within which these creatures lived are explained in a manner that brings them to life. Two particularly striking examples are the coverage of the Weymouth Bay Pliosaur, now displayed in the Dorset County Museum, and the Etches Collection at Kimmeridge *[a report on which is featured in the* Wessex Footnotes *issue for December 2016, pp7–8 — Ed.]*

An innovative feature is six suggested itineraries for fossil walks along various parts of the Jurassic Coast, which give details of local museums and other geological points of interest that you may like to visit while you are in the general area. In this section, some basic principles of geology are introduced in layman's terms (for example, biostratigraphy and the formation of oil) in a manner that holds the interest of all readers irrespective of their knowledge.

Part Four deals with fossil collecting. It starts by giving a brief history of fossils, commencing with myths believed about them prior to the 19th century, before people like Mary Anning revealed them for what they actually were — plants and animals from deep time. There then follows a comprehensive explanation on how to collect, prepare and keep fossils. At the back of the book is a useful list of websites and contact numbers for various museums and groups, together with a pull-out poster that illustrates the tree of life of the Jurassic Coast.

This book is very good value at £14.95 and I would recommend it for anyone who has an interest in fossils, irrespective of age, particularly if they intend to visit the Jurassic Coast.

— Mark A. Barrett, BSc Hons Natural Sciences (Open)

OUGS AGM 2016 Geoff Brown Memorial Lecture

Tambora 1815, super-volcano eruptions, and the future volcanic threat

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1. Introduction

While the 1883 Krakatoa eruption is coincident in many people's minds with the ultimate in volcanic devastation, most remain unaware of the great explosion of another Indonesian volcano, Tambora (Fig. 1) — five times bigger and nearly 70 years earlier. This is hardly surprising given the kick-start that the burgeoning global telegraph business gave to the Krakatoa blast, spreading the news swiftly across the planet and installing it permanently in the catastrophe mindset. When Tambora blew itself apart in 1815, the first working telegraph was still 12 months away, so word of the event leaked only slowly and sporadically in the direction of Europe and North America. At a time when it took 45 days for a letter to reach London from Singapore, knowledge of Tambora seeped rather than exploded onto the world stage, and general awareness of the event has suffered ever since. Nonetheless, the impact of Tambora on the climate and on society greatly outweighed that of the lesser blast at the other end of the 19th century.

Scoring a seven on the Volcano Explosivity Index, the 1815 Tambora eruption was the largest in recorded history. As well as causing devastation on Sumbawa and neighbouring islands, the legacy of the blast was a serious deterioration in weather across Europe and eastern North America, which resulted in wholesale harvest failure. This in turn triggered famine and civil unrest in what economic historian, John Post, has termed the "the last, great, subsistence crisis in then western world." The severe impact of the Tambora eruption on agriculture and its deleterious ramifications hold important lessons for future volcanic events on this scale and flag potentially serious consequences for economy and society.

2. Setting the scene

The global volcanic threat is significant, with more than 1,550 volcanoes having erupted during the Holocene (approximately the last 10,000 years). In addition, there is perhaps a comparable number of volcanoes that show no evidence of Holocene activity, but which may have the potential to erupt again. Around 550 volcanoes have erupted in recorded history, of which between 50 and 70 are active every year, and on any single day, about 20 volcanoes can be expected to be in eruption. Indonesia is the most volcanically active nation on the planet, boasting 78 historically active volcanoes, including — in Krakatoa and Tambora — two of the biggest volcanic explosions of modern times.

While the absence of effective global communication hindered the immediate spread of news about the Tambora eruption, the presence of a particular individual ensured that knowledge of the event was ultimately preserved. British diplomat, Thomas Stamford Bingley Raffles — later Sir Stamford Raffles — was, at the time of the eruption, the Lieutenant Governor of Java, and so perfectly placed to record the details of the event and its local consequences, which he did in his *History of Java*, published in 1817. Further details of the eruption are contained in Raffles' biography, written by his daughter Sophie and published in 1830, and in issues of the *Asiatic Journal* from 1816. These contemporary sources provided invaluable material for a 2003 review of the eruption and its impacts by Clive Oppenheimer and a recent (2014) book marking the bicentennial by Gillen D'Arcy Wood.

Figure 1 Aerial view of the summit of Tambora (courtesy Jialiang Gao. Licensed under the Creative Commons Attribution-Share Alike 3.0 Unported; https://en.wikipedia.org/wiki/Mount_Tambora#/media/File:Caldera_Mt_Tambora_Sumbawa_Indonesia.jpg).

3. Anatomy of a catastrophe

Tambora is a classic subduction-related stratovolcano located above the Java Trench. With an age of 57,000 years, it is also relatively young. Nonetheless, it formed an impressive mountain and prior to the 1815 eruption is estimated to have stood 4,300m tall, making it, at that time, the highest peak in the East Indies. It certainly would have towered above the surrounding landscape and dominated the northern end of Sumbawa's Sanggar Peninsula. It is highly likely that those living in the volcano's shadow had no idea that the volcano was active and presented a threat to life and livelihoods; the last eruption occurring more than 2,500 years earlier in 740 BC.

The first signs of unrest are recorded in 1812, indicating that fresh magma was on the move within the volcano; but it was another three years before this reached the surface. It did so violently on April 5th, with a major blast that hurled a column of ash tens of kilometres into the atmosphere. Just five days later the climactic phase of the eruption began at 19:00 (local time) on April 10th, and lasted for close to 24 hours. Activity then slowly subsided until the eruption ended sometime the following month. While the local and regional impacts were immediate, remote climatic effects took longer to take hold, so that it was 1816 that became known — in Europe and eastern North America — as 'the year without a summer'.

Tambora has been relatively quiet for the last couple of centuries; the last minor eruption occurring in 1967. Recently, however, the volcano has shown increased signs of unrest, resulting,

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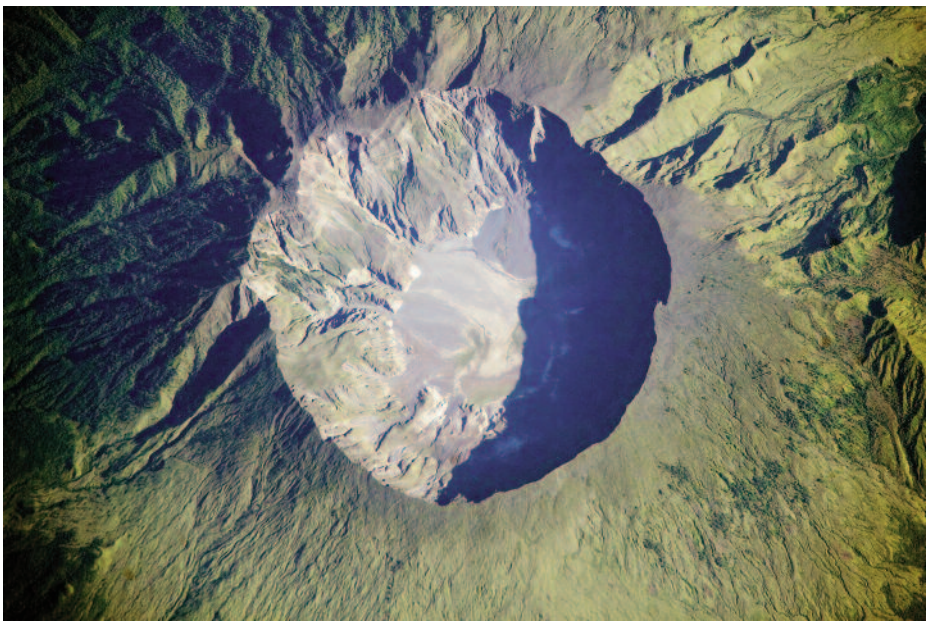

Figure 2 Vertical view of the Tambora summit caldera formed in 1815, taken by the NASA Expedition 20 crew (courtesy NASA; http://eoimages.gsfc.nasa.gov/images/imagerecords/39000/39412/ISS020-E-06563_lrg.jpg).

in 2013, in the alert level being raised to 2 (on a scale of 1–4). While another blast on the scale of 1815 is unlikely in the extreme, a moderate eruption in the near- to medium-term is certainly not out of the question.

The numbers of the 1815 explosion are truly staggering. One hundred and forty gigatonnes of pulverised rock was ejected, mostly within the 24-hour long climactic phase. The volume of erupted material was on the order of 100km^3, translating to a dense rock equivalent (DRE) of *c.* 41km^3. Ash and pumice left the vent at an estimated rate of 1.3km3 an hour, feeding an eruption column that climbed to an altitude of 43km. The biggest detonations were heard more than 2,000km away and ash fall was so heavy that many places within 600km of the volcano were in complete darkness for up to two days. Much of Sumbawa was buried beneath 0.5m or more of ash, while pumicious pyroclastic flows (ignimbrite flows) scoured the landscape up to 30km from Tambora's summit. Fully 95 per cent of the ejected mass took the form of pyroclastic flows; the remaining five per cent taking the form of ash making up a Plinian eruption column. The entry of pyroclastic flows into the sea also generated tsunamis with run-ups as high as 4m, which caused considerable damage to some coastal communities.

The eruption itself is estimated to have taken *c.* 12,000 lives, mainly due to immolation or asphyxiation by pyroclastic flows. Famine following the destruction of crops and loss of livestock resulted in the loss of a further 59,000 lives as a consequence of starvation and disease, including respiratory problems and fluorine poisoning. The eruption took its toll on the volcano too, reducing its height by 450m and opening a caldera 6km across and a kilometre deep (Fig. 2).

4. The Year Without a Summer

The Tambora eruption is best known not for its devastating impact on the local population and environment, but for the manner in which it affected the climate and impinged detrimentally upon countries half a world away. The eruption lofted an estimated 60 megatonnes of sulphur gases into the stratosphere, forming a veil of sulphate aerosols that significantly reduced the level of incoming solar radiation. The resulting cooling of the troposphere and surface reached a peak of about 1°C in 1816. The same year also saw the second coldest northern hemisphere summer in 600 years; just the first of a string of anomalously cold summers that persisted for at least three years. Analysis of the temperature curve for the time indicates another significant fall in northern hemisphere temperatures in 1812, which is assumed to have been triggered by another large volcanic event that has yet to be identified. The appalling summer of 1816 seems, therefore, to have been a legacy of the cooling effects of these two eruptions combined.

In eastern North America, the weather in the year following the eruption was dire. Across New England, severe frosts and snow were still evident in June, while 300mm of snow fell in Quebec. Hard frosts continued throughout the summer months, halving the growing season and leading to almost total crop failure across the region. Farm losses were so great throughout the north-eastern states of the US that they supposedly contributed towards the first big migration to the interior.

The situation in Europe was, if anything, worse. Summer temperatures in 1816 were up to 3°C down on the 1951–1970 average, and this, alongside extremely wet weather, drove harvest failure on a scale comparable to that experienced in North America. The European economy was still struggling to recover in the aftermath of the Napoleonic Wars, and the consequences of a failed harvest conspired to promote unrest among an already fractious population. Bread prices reached levels that were unaffordable even to those on an average wage, prompting riots in the UK, Germany and elsewhere. Disease, in particular typhus, was rampant, taking as many as 40,000 lives in Ireland alone.

The conditions of economic hardship and social unrest continued at least until 1817, spawning financial turmoil and depression across post-Napoleonic Europe. They also probably played a part in the last armed uprising in England, which began in the Derbyshire village of Pentrich in June 1817. From here, up to 300 disaffected and armed men, led by Jeremiah Brandreth, set off towards the seat of government in London. The column was supposed to sweep up more supporters on the way, but they were informed upon and only made it as far as the village of Giltbrook in the next county — Nottinghamshire. Here the march was broken up by soldiers and the ring leaders captured, later to be hanged for high treason or deported.

The aftermath of the 1815 eruption also appears to have had some other unlooked for consequences. The gloom and cold of the 1816 summer is widely held to have played a key role in prompting Mary Shelley to begin her great gothic masterpiece, *Frankenstein*, and to push Byron to pen his bleak poem, *Darkness*. In Germany, the prohibitive cost of animal feed in 1817 persuaded Karl von Drais to invent the 'Dandy Horse', or Draisine, a pedal-less, two-wheeled vehicle that ultimately gave

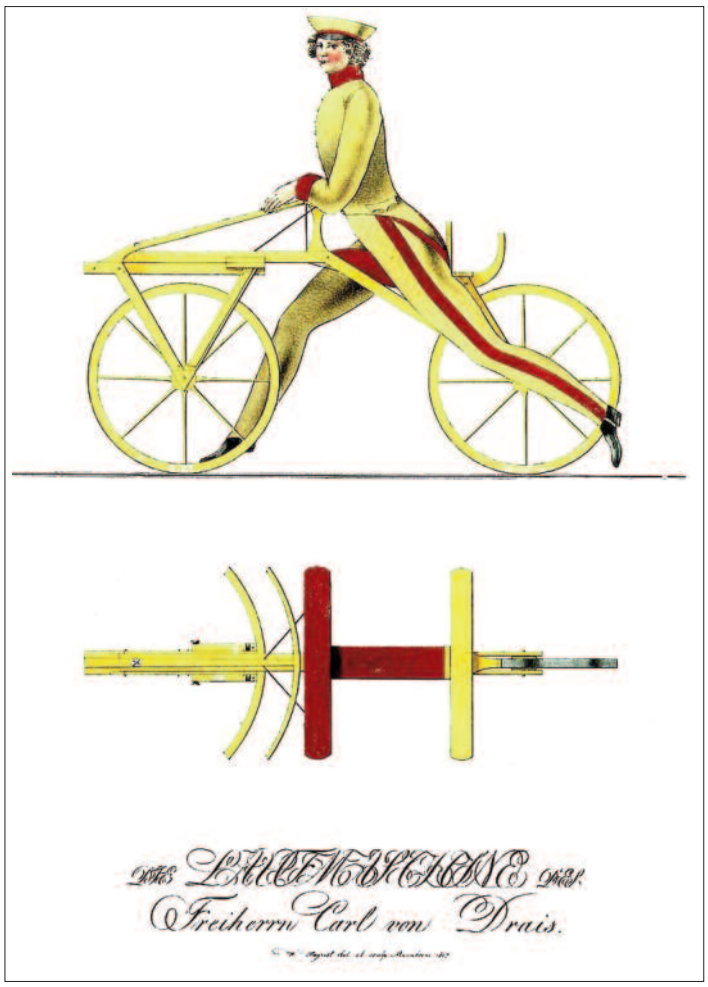

Figure 3 The Dandy Horse or Draisine, invented in 1817 by Karl Drais (https://en.wikipedia.org/wiki/Dandy_horse#/media/File:Draisine1817.jpg).

rise to the modern bicycle (Fig. 3). The brilliant sunsets of some of J. M. Turner's landscapes have also been attributed to the effects of volcanic dust in the atmosphere in the years following the eruption, although this is difficult to verify.

5. Tambora in context

There is no doubt that the 1815 Tambora eruption constituted a major volcanic event that had severe consequences, both locally and across the world. As volcanic eruptions go, however, it was far from the biggest. On the Volcano Explosivity Index (VEI), on which the scale of volcanic events is measured, the Tambora blast scores an impressive 7, a ranking reserved for eruptions that eject a volume on the order of 100km^3 of material. The VEI is logarithmic, so that a VEI 7 is ten times bigger than a VEI6 and ten times smaller than a VEI8. The 1815 eruption was therefore about 100 times bigger than the 1980 eruption of Mount St. Helens (Washington State, USA) (VEI5) and 10 times bigger than the 1991 eruption of Pinatubo (Philippines) (VEI6). On the other hand, it pales into insignificance when compared with VEI8 events (*see* Table 1). Such events erupt at least 1,000km^3 of material and include the 640,000y BP eruption of Yellowstone (1,000km^3), the 74,000y BP Toba (Indonesia) blast (2,800km^3) and the colossal 30-million-year-old Wah Wah Springs eruption (5,000km3) in Utah, USA.

Such so-called 'super-eruptions' are extremely rare and probably have return periods as long as 50,000 years or even longer. Nonetheless, they are important from a risk viewpoint, as they have massive impacts at the global scale. Volcanoes capable of hosting super-eruptions require a certain magma 'recipe' and so are also geographically restricted. Magma must be sufficiently rich in silica to promote high viscosity and gas contents and severely restrict bubble expansion so that enormous overpressures accumulate as magma rises towards the surface. Conditions also need to prevail that allow or promote the accumulation of a very large body of magma and then permit its release (or at least the release of a substantial fraction of it) in one go. Broadly speaking all the conditions required for a super-eruption are satisfied primarily around the Pacific Rim and in South East Asia.

The huge volumes of material ejected require the climactic phases of super-eruptions to have durations of a week or more, resulting in regional devastation, but it is their remote consequence that attract the greatest interest. In this context, they are like Tambora writ large. The quantity of sulphate aerosols that load the stratosphere after a super-eruption are prodigious and may reach 5,000 megatonnes. This is sufficient to cause a global temperature fall of several degrees Celsius, triggering what has become known as a 'volcanic winter.'

The Yellowstone super-eruption of 640,000y BP saw ash fall as far away as what is now Los Angeles (California) and El Paso (Texas). Even 1,500km from the eruption site, compacted ash deposits were 20cm thick. Ashy horizons in drill cores from the Caribbean attest to wholesale reworking of the ash fallout by the major river systems, which may well have become clogged resulting in widespread flooding. The impact of the eruption on global temperatures has not been established, but would have been considerable.

Nearer to the present day, the impacts of the Toba (Indonesia) super-eruption at 74,000y BP — which was almost three times bigger than the Yellowstone explosion — are even more impressive. In the process of excavating one of the largest volcanic craters on the planet, 100mm or more of ash was dumped on at least one per cent of the Earth's surface. Five gigatonnes of sulphate aerosol introduced into the stratosphere caused northern hemisphere temperatures to tumble by 3–5°C and brought about a severe volcanic winter that lasted for five to six years. There were immediate temperature falls close to or below zero degrees centigrade in the tropics, and hard freezing at mid-latitudes, while modelling of the effects of the eruption suggest that perhaps one-third of the planet could have been covered by ice and snow. The consequence for our human ancestors may have been

Table 1 Selected VEI ('super') eruptions

volcano	*location*	*eruption date ('000y)*
Cerro Galan	Argentina	2200
Yellowstone	USA (Wyoming)	2000
Toba	Indonesia (Sumatra)	790
Long Valley	USA (California)	700
Yellowstone	USA (Wyoming)	640
Toba	Indonesia (Sumatra)	74
Oruanui	New Zealand (North Island)	26.5

close to terminal, and there is a school of thought that a human population bottleneck at around this time may be traced to the eruption. It appears that the human population may have been reduced to a pool of just a few thousand individuals for a couple of centuries, bringing our race within a whisker of extinction.

6. The next Tambora

The rarity of super-eruptions counts against such an event happening in the short- to medium-term, although this can never be completely ruled out. The probability, in the not to distant future, of another Tambora-scale blast is, however, significantly greater. One estimate of the likelihood of another Tambora is 1 in 10 in the next 50 years, but the return period for climate perturbing eruptions may be as short as a few centuries (*see* Table 2). Bearing this in mind, how would we fare if another eruption on the scale of Tambora happened today?

In relation to widespread harvest failures, the received wisdom is that globalisation will make it easier to cope. It could well be argued, however, that this very interconnectedness of world markets could make things worse. Harvest failures in North America, Europe and perhaps elsewhere could be expected to drive huge hikes in the cost of grain, pricing out many — particularly in developing countries or in the disadvantaged of industrial societies. In addition, competition for reduced food commodities could be expected to drastically reduce the range of available products, compromise supply and distribution systems and bring about a collapse of the 'just-in-time' production and delivery mechanism so beloved of large, modern food suppliers. As in the years following Tambora, the end product could be serious civil unrest, but potentially on a far wider scale.

Clearly, there will be another climate-perturbing eruption on the scale of Tambora, or even larger, and the key to coping successfully with the consequences is to be prepared. Unfortunately, while at least some elements of the scientific community might be aware of the future volcanic threat, key stakeholders are not. Governments have other day-to-day priorities and tend to have time horizons limited by the date of the next election. Aid agencies have enough on their plates with countless wars and civil problems, while emergency managers and planners are inevitably concerned with more immediate situations. All this translates into a relationship with hazardous natural phenomena — including volcanic eruptions — that is dominated by a reactive rather than proactive approach; in other words response still dominates thinking, much to the detriment of effective preparedness. The 2010 Eyjafjallajökull eruption provides an excellent example of this. We only need to look back to 1947 for the last time that Icelandic ash impinged upon UK airspace, yet the National Risk Register contained no mention of a threat from Icelandic eruptions. As a reaction to the aviation mayhem arising from the events of 2010, Icelandic ash hazard has now been added to the register.

Table 2 Selected eruptions of the last 10,000 years, sufficiently large to have had significant climate-perturbing effects

volcano	*location*	*eruption date*
Kurile Lake	Russia (Kamchatka)	8470y BP
Crater Lake	USA (Oregon)	7600y BP
Kikai	Japan (Ryukyu Islands)	6300y BP
Taupo	New Zealand (North Island)	AD 180
Baitoushan (Mt. Paektu)	China-North Korea border	AD 1030
Unknown	—	AD 1258
Kuwae	Vanuatu	AD 1452
Tambora	Indonesia (Sumbawa)	AD 1815

Given that a major eruption on a scale sufficient to have a significant impact on the climate is certain at some point in the future, is there anything in the pipeline? Two volcanoes that are well worth watching are Uturuncu in Bolivia and Laguna del Maule in Chile. Both have hosted enormous eruptions in the past and both are once again demonstrating clear signs of restlessness. At Uturuncu, a 70km wide bulge has been growing steadily since the early 1990s, as fresh magma intrudes beneath the volcano. Farther south, the Laguna del Maule volcano is swelling at the astonishing rate of 250mm a year above a large body of magma just 6km down. There can be no certainty, in either case, that such unrest will translate to an eruption, nor that if it does the eruption will be large enough to seriously impact upon the climate, but the risk is not insignificant. So, in conclusion, do keep smiling … but don't say I didn't warn you.

7. Sources and further reading

D'arcy Wood, G. 2014 *Tambora: the Eruption that Changed the World*. Princeton: Princeton University Press

East India Company. 1816 onwards *The Asiatic Journal and Monthly Miscellany*

Harrington, C. R. (ed.) 1992 *The Year Without a Summer? World Climate in 1816*. Ottawa: Canadian Museum of Nature

Oppenheimer, C. 2003 'Climatic, environmental and human consequences of the largest known historic eruption; Tambora volcano (Indonesia), 1815'. *Progress Phys Geogr* **27**, 230-–59

Post, J. D. 1977 *The Last Great Subsistence Crisis in the Western World.* Baltimore: John Hopkins Press

Raffles, Sir T. S. 1817 *The History of Java*. London: Black, Parbury & Allen

Raffles, Lady S. 1830 *Memoir of the Life and Public Services of Sir Thomas Stamford Raffles, F.R.S. &c., particularly in the government of Java 1811–1816, and of Bencoolen and its dependencies 1817–1824: with details of the commerce and resources of the eastern archipelago, and selections from his correspondence*. London: John Murray

OUGS Symposium, Exeter 2016: How the West was Made

Beneath Cornubia: public perceptions of the geological subsurface in the South West

Prof. Iain Stewart

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[OUGS Exeter Symposium: How the West was Made; original transcription by Rosemary Darby from the Symposium recording; edited by Prof. Stewart and POUGS Editor David M. Jones.]

RESEARCH WITH PLYMOUTH UNIVERSITY
Between a rock and a hard place
Communicating contested geoscience to the public
Act I - The Underworld

Introduction

I want to begin with an issue that is very familiar to all of us: "What's down beneath us? After all, as geologists that is 'our world' ". It is a world that we read about and we go on field trips to uncover, and it is a world that is pretty familiar if you have been a professional geologist. Of course, it is very unfamiliar to 'normal' people. That is because you and I are mentally unusual. Indeed, we celebrate our unusualness. You know this to be true because you have sat and stood in cafes and bars and talked about geology and seen the reaction of normal people. So we realise that other people do not think about the subsurface. You can test this by asking non-geologist friends, "What is beneath our feet"; and it quite interesting to see the blank reaction you get.

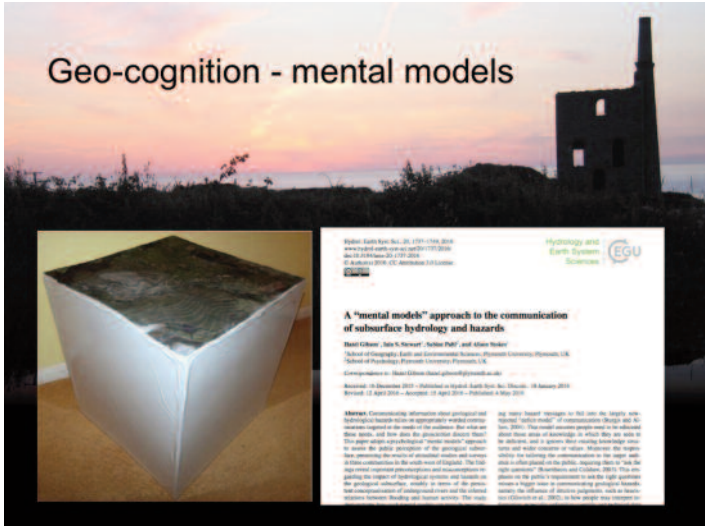
I became interested in this question because of geothermal energy. Down in the South West there used to be a geothermal project — the 'Hot Dry Rocks' project in the 1970s — which was later mothballed. But in the last few years the prospect of geothermal has reared its head again and there is a number of projects that are proposing to drill down into the granite, more specifically into some faults in the granite to get hot fluids moving and generate heat and perhaps power. And so there was a lot of interest in telling communities about this potential geothermal energy, and what was interesting was talking to the geologists who were doing it. One said, "Well it's quite funny because when we talk to people they'll say things like, 'Well I'm a bit worried about this because when you drill into the granite, I'm worried the magma's going to come up! That's why I'm going to object to you doing geothermal — I don't like the idea!' " Well, of course, we had a giggle at that, but as I was driving home I thought, in a way that is quite good because they know that granite comes from a magma — that's a tick — and they also know there is heat involved because it is geothermal and also hot; in a way, the only thing that is a bit ridiculous is that they do not know the melting temperature of granite. Something that at first seemed to be crazy, actually, is not all that odd. So, I got interested in this and decided to get a research student onto it.

'Geo-cognition' of the subsurface

The resulting research project is a co-operation between me as a geologist, a colleague at Plymouth who is a cognitive psychologist and Hazel Gibson — our joint PhD student. Together, we have been looking at something called 'Geo-cognition', which in this case is essentially what the public think about the subsurface. Hazel has been using what is called a 'mental models approach' — a technique in psychology involving semi-structured interviews: chatting to people, having conversations, asking them questions as a way of revealing the way they think about things. Depending on the responses and the words that come back, the researcher tries to create a mental model of how people think about a certain concept or idea, in our case — the subsurface.

What is interesting then is that Hazel has also done this with experts, with geologists; the idea is to compare what an expert geologist sees in some subjects with what a non-geologist sees in those same subjects. And one of the ways, and perhaps the most interesting aspect that Hazel came upon earlier, is that the language in some circumstances is quite difficult for people regarding the words that they use and we use. So, she came up with the idea of using this cube (Fig. 1): on top is an image of one of the three areas we were dealing with, a silhoutte of Carharrack, in Cornwall — tin-mining country; the other two

Figure 1 The cube model — exploring 'geo-cognition' of the subsurface.



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areas are Hemerdon, just outside Plymouth, where tungsten mines just opened; and a control site in North Devon, which does not have any significant geological interest.

So this image of Carharrack is about 5km × 5km across. You can see the topography has been moulded and cast so the participants can look at it and recognise the roads, the houses, and the school, in their area. Hazel then asked them questions about what is beneath their feet. I am only going to talk about the responses from Carharrack, an area that has had a history of mining; so there is a culture of mining, with lots of evidence of mining in the landscape, which is important for tourism. In other words, mining is a big deal. And this is also an area where there had been some exploratory work done, because this is where there is an interest in geothermal drilling.

This cube shows an expert model of the area. You can see that for this expert, one of the key elements below ground is the presence of faults — represented by these straight lines are vertical faults, cutting obliquely across the figure (Fig. 2). Also, you can see written there on the cube the word 'killas', the word 'granite', and '1 kilometre' depth; also '5 kilometre', and 'fault'. These are the bare structural elements that the expert sees. This is the skeleton, if they had had more time they could have drawn a beautiful diagram, but these was the basic elements.

What was interesting about this example was that every expert Hazel interviewed used two sides of the cube. However, not a single member of the public used a second side. And that immediately tells us one thing, which is that we [geologists] think spatially different from normal people. That is because those of us who have gone through a geology degree — an OU degree or whatever — realise very quickly that you have to think in three dimensions. Geology does not make sense if you do not think in three dimensions. We gradually train our brains to think in a specialised way, wiring them to make sense of relations in 3D. But that is not typical of 'normal' people. So that immediately puts us in a slightly different place.

Alongside their sketch (Fig. 3) is this quotation from an interviewee in Carharrack, "… so you go down and down until you hit the hot rocks and the coal there and it's heat from radiation, these are the miners virtually in the nude and you can see why these miners are stripped to the waist and mining away in the heat." Now, in their sketch they have written the words 'soil', 'subsoil', the 'heather and gorse' on the top, and he depicts the mine in the granite, with the shaft and the stopes, annotated with the terms 'hard rock', 'Devonian', 'granite', 'veins of gold, tin, copper,

Figure 2 An expert's 'geo-cognition' of the subsurface cube model.

zinc, silver'. Hazel asked this interviewee, "Well, that's the mine, that's the human bit; what about the rock? What's actually there?" The interviewee picked up a red pen and wrote 'dark'. In other words, they could think quite imaginatively and accurately about the human side of the mine, but when they were actually asked to step outside this idea — to the rock into which it was going — the only thing they could think of is that it is dark.

Another interviewee quotation says, "…down to the very bottom of the Earth, that's because where it was all broken down even more and I presume that's where the heat of the earth is." Figure 3 is that person's sketch, showing the ground surface, which is interesting because that is *their* ground surface, but the top of the cube is the real ground surface. Here is someone who has not actually realised what the physical cube actually represents — he or she has drawn an artificial ground surface; also a whole series of layers labelled with 'industrial age', 'agriculture', 'bronze', 'dinosaurs', 'Devonian', 'Cambrian' etc; *and* the core of the earth. Then, apparently, they thought, 'that's ridiculous', so re-drew it (Fig. 4). Now this interpretation, for a geologist, is funny. But for a lay person, if you are told there is heat… well, heat comes from the core …and the core is down there — in this case, just a few kilometres down. After all, that must be what the geothermal drilling is trying to get at.

Some [non-geologist] interviewees were even more vague. Figure 5 *(opposite)* is another example from Carharrack. This depiction is interesting with its buildings depicted. When Hazel asked why the buildings were inside the Earth, the person said these were mine buildings from a long time ago covered up by

Figure 3 An interviewee's subsurface interpretation of the cube model.

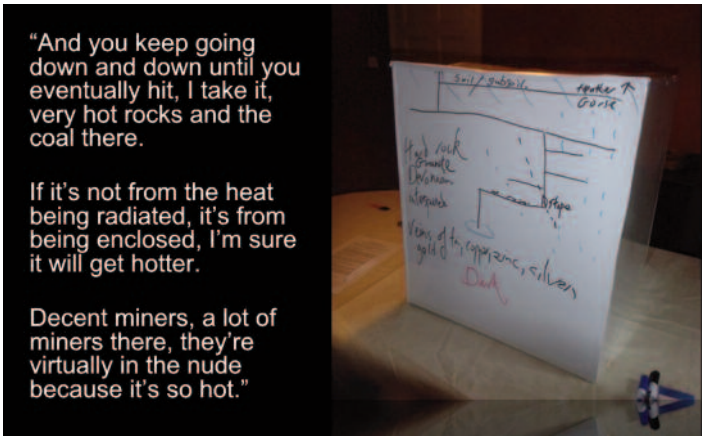

"And you keep going down and down until you eventually hit, I take it, very hot rocks and the coal there.
If it's not from the heat being radiated, it's from being enclosed, I'm sure it will get hotter.
Decent miners, a lot of miners there, they're virtually in the nude because it's so hot."

Figure 4 An interviewee who had 'second thoughts'.

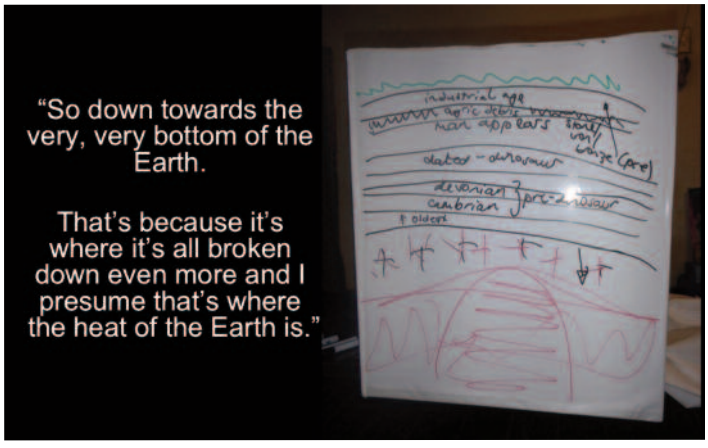

"So down towards the very, very bottom of the Earth.
That's because it's where it's all broken down even more and I presume that's where the heat of the Earth is."

Figure 5 An interviewee who pictured subsurface buildings on the Carharrack cube model.

more rock. For some the question was so difficult that they just put in some pictures of granite and some sedimentary rock. Figure 6 is another cube depiction with some layers vaguely drawn, and with the words 'warm 70 degrees'. Hazel asked, "How far down do you go until the hot stuff?"; and the reply was, "Probably a thousand miles deep — I don't know, I can't really visualise it."

For me, this is all quite fascinating because these are people living in this area and taking part in the survey because presumably they are interested in the topic. But they are really blank canvases in terms of what is beneath their feet. And that, really, is the essence of the problem: people have never been asked to imagine the subsurface before. When they *are* asked, they realise that they do not have the technical knowledge or the conceptual understanding to grasp it. They really have no reference markers for the subsurface. One of the things that comes out is a confusion of depth — of how deep things are, particularly whether it is thousands of miles down before you get to core heat, or else the core is within a very short distance from the surface. So this idea of the underground heat is a problem.

One of the other most common misconceptions among interviewees was about underground water, about rivers flowing through. People made connections to surface rivers and springs. To them, it was very simple: because there are rivers on the surface and water trickles down, there must be rivers running through the subsurface. This concept turns out to be really quite crucial when people are talking about worries concerning fluids flowing in the subsurface — when talking about fracking, for example, because they are imagining rivers.

You may wonder about where all these misconceptions are coming from. Then you remember that we geologists are not normal — we have had training that gives us a sense of what is down there in the subsurface. Without this training, where would a person get the information about the subsurface ? You might get it from a few strange documentaries like mine, but other than that, where would you get it? How much is in the school curriculum about the subsurface? The reason non-geologists think there are fluid pathways and conduits in the subsurface is because when they see anything about the subsurface it is of mining and shafts and the like; or it is limestone cave systems where there are underground rivers.

So, either people's minds are full of nothing about the subsurface or are full of misconceptions, which in some instances could be more problematic. Remember this is Carharrack — mining territory. In writing up her thesis Hazel is finding that there appear to be differences between Carharrack and her interview other sites.

At a recent conference someone asked, "This is the South West — what would happen if you did this in London? What would they think about the subsurface under there if they don't have a connection with the natural world? It would be even more extreme." What I think we are learning from this research is that people really have no idea about what goes on in the subsurface and that is really a big issue for those of us who are talking about the subsurface. We might assume that people lack some of the technical knowledge, but I think the sheer scale of disconnect has taken us by surprise.

'Tampering' with the subsurface

Another aspect is how 'scary' the subsurface is to people. After all, if they take their cues from popular culture, then the 'underworld' is not a nice place. It is a hidden world into which things are seeping down. The subsurface is viewed as an alien, dangerous, unfriendly place. And that has a direct implication to those of us who study the subsurface — if we go into the subsurface, we are going down where we should not be. Psychologists have looked at this idea in various ways. Figure 7 is a diagram that

Figure 6 Q: "How far down do you go until the hot stuff?" A: "Probably a thousand miles deep — I don't know, I can't really visualise it."

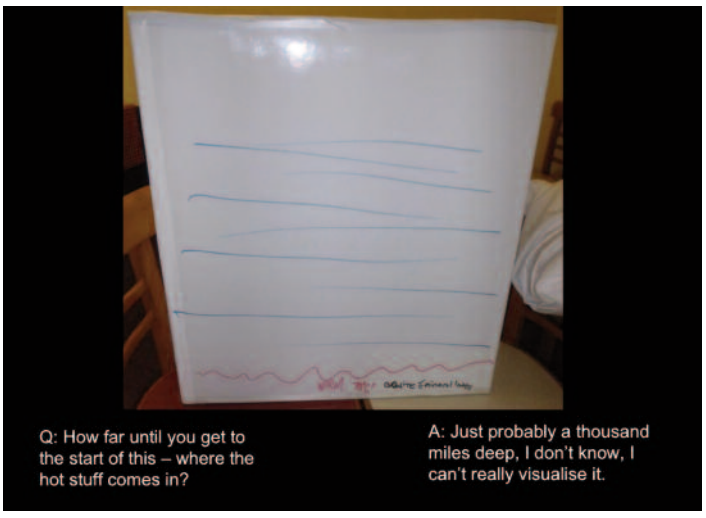
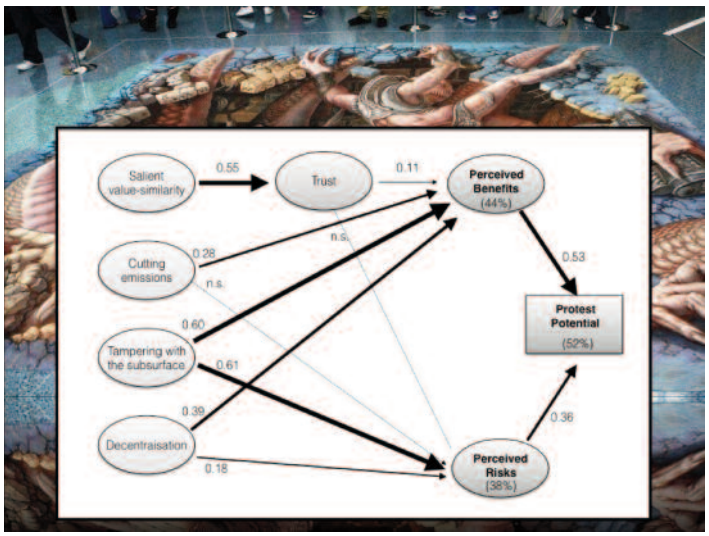

Q: How far until you get to the start of this – where the hot stuff comes in?
A: Just probably a thousand miles deep, I don't know, I can't really visualise it.

Figure 7 Public perception of Carbon Capture in the subsurface.



shows the public's acceptance of Carbon Capture and Storage (CCS). It involves taking CO_2 from power stations and taking it in pipes to inject it down into some sort of reservoir — a sandstone reservoir or a saline aquifer reservoir — to store it permanently underground. CCS is one of the big ideas about engineering for climate change, and so this is a potential for people to protest. We can perceive benefits; we can see risks. Overall, one concern dominates what people think is important: the idea of humans 'tampering with the subsurface' explains 60% of the variability of what sets people's perceptions about CCS.

People seem broadly uncomfortable with the notion that humans are interfering with the natural world. It is almost as if somehow there is this world that is pristine down there, and that these interventions to store waste, or to capture carbon, or of fracking, or of tapping geothermal sources, will take us into places where humans should not be. Now, if you are a geologist that seems perverse because we know that the subsurface is messy, very fractured, and has lots of fluids going through it. Indeed, the rocks have been through much worse than humans could throw at them. But if you have not thought about it in geological terms, then why would you not think this is a pristine world that humans should keep out of?

I think this 'pristine world' idea is important in the context of carbon capture and storage, which is one of the ways that the UK could use depleted oil fields in the North Sea to 'reverse engineer' the pipelines and send CO_2 back from power stations into offshore subsurface reservoirs. This diagram (Fig. 8) shows the results of a study done about public perceptions of CCS. For each question, blue is people that say 'no', red is for 'yes' and white is 'don't know'.

The first question is, "The deeper you drill into the subsurface the higher the pressure gets — who thinks that is correct?" *[Ed: The question was put to the audience of OUGS geologists, who in a show of hands answered 'yes', and were correct.]* But actually only half of the general public say 'yes'; nearly 17% say that this pressure increase is not correct; and a big proportion really 'don't know'. I would say that ideas about internal earth heat and pressure are a very basic aspect in geology! So much of what we know about geology comes from the idea of geothermal gradient and geo-pressure gradient. But for people not thinking like us, this concept does not naturally come to mind.

The reason that this is important comes in the next question: "The natural pressure and depth at which CO_2 is injected is so high that it is kept as a liquid — who thinks that is true?" [*Ed: Again, put to the audience of OUGS geologists.]* It is true, but most of you did not realise that because it is very technical; essentially, due to the pressure at depth CO_2 is injected as a sub-critical liquid. Of course, many people think, "Well, CO_2 is a gas so how can it possibly be a liquid?" If you do not grasp the importance of pressure, then how could CO_2 be anything else but a gas?

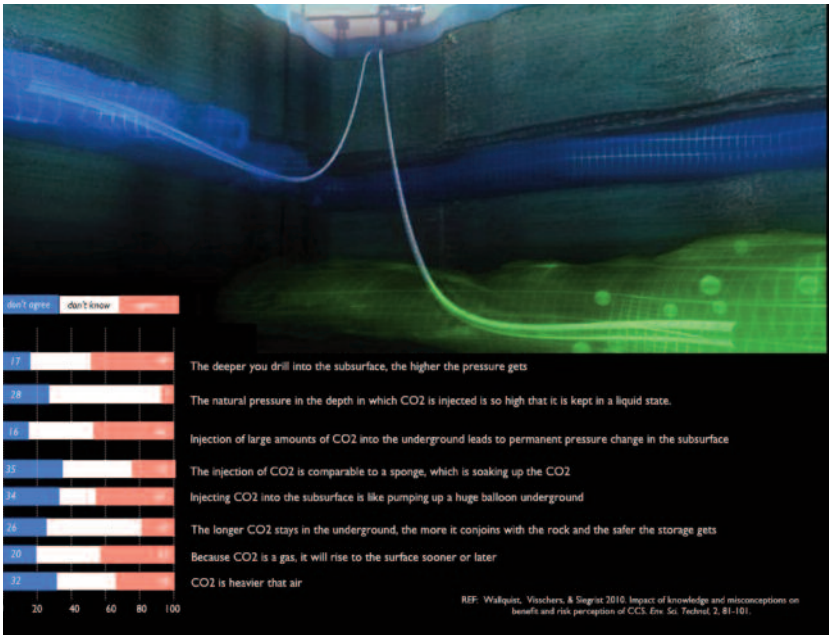
So, one basic misconception starts to create other ones. Another interesting 'question' is: "The injection of CO_2 is comparable with a sponge that is soaking up CO_2 ". Now, this would be a geological description of Carbon Capture Storage in which the CO_2 goes into the grain spaces, into the pores, the fractures and fills up the rocks; the carbon gets bound chemically — presumably to sandstone and material like that — and is basically soaked up. About a quarter of the public in this survey thought 'yes', that sounds right. However, far more — 45% — agreed that injecting CO_2 into the subsurface was more like pumping up a huge balloon underground. That is because they are not sure about how pressure affects a gas. . And, of course, this presents a problem: What is going to happen when you blow up a balloon underground? Of course that is when people start to worry — "What if it pops?" If it bursts there will be a catastrophic release of all the CO_2 that has been put underground as waste. So people say, "I don't like it!"

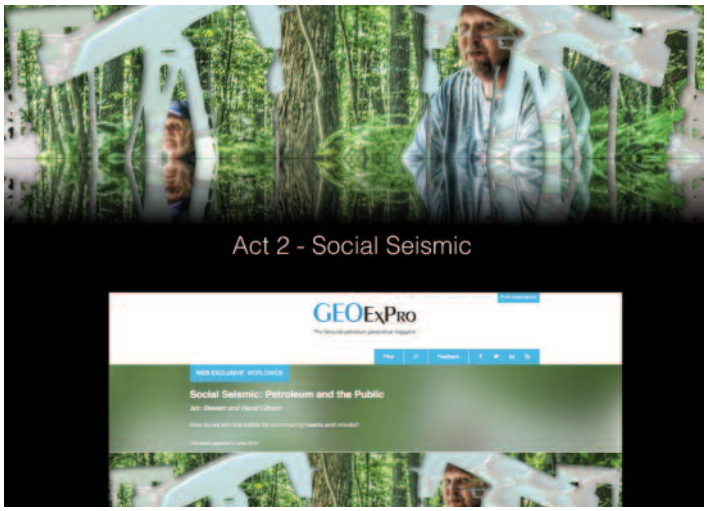
The wider implication is that we are trying to persuade the public that CCS is a technology is a good thing. There is a big argument now that government has slashed the subsidies for CCS in the UK — has slashed the research funds to develop it — and the chances are that it will stall. And yet this is one of the only ways that we can engineer to combat climate change. But to implement it, the public will have to buy into the idea. The public will have to be happy with carbon storage, either underneath them onshore, or offshore. Some of this debate is very technical and yet what I am arguing is that the actual key knowledge on which we start to argue the case is very, very basic. We face a huge disconnect between the level of technical information that geologists feel the public need to understand to be able to say, "Yes I think this is a good thing" and the level of technical knowledge they apparently have — because you need a public mandate to be trying some of these very uncertain technologies.

The solution then becomes, "Well, obviously what we need to do is to tell the public more about this." The public lacks this knowledge of the geological connections, so my job as a communicator is surely to educate the public about it.

I do not think that is right at all, however! I do not believe educating the public is the way forward. Instead, I want to talk about what I call 'social seismic', which is imaging the 'hidden' public — in other words, trying to find out who the public are, how they think, and how we can get our message more effectively to them. It forms the basis of a recent article in the magazine *GeoExPro* (also on-line as a web page article), which looks at this problem from the oil and gas perspective.

Figure 8 Public perceptions of Carbon Capture and Storage (CCS).


don't agree
don't know
17
28
16
35
34
26
20
32
20
40
60
80
100
The deeper you drill into the subsurface, the higher the pressure gets
The natural pressure in the depth in which CO2 is injected is so high that it is kept in a liquid state.
Injection of large amounts of CO2 into the underground leads to permanent pressure change in the subsurface
The injection of CO2 is comparable to a sponge, which is soaking up the CO2
Injecting CO2 into the subsurface is like pumping up a huge balloon underground
The longer CO2 stays in the underground, the more it conjoins with the rock and the safer the storage gets
Because CO2 is a gas, it will rise to the surface sooner or later
CO2 is heavier that air
REF: Wallquist, Visschers, & Siegrist 2010. Impact of knowledge and misconceptions on benefit and risk perception of CCS. Env. Sci. Technol. 2, 81-101.



Fracking, science and 'the public'

Which brings us, inevitably, to 'fracking', one of the headline news items at the moment for geology. Anyone who has mentioned to friends and colleagues that they are interested in geology has been asked, "What do you think of this fracking business?" Figure 9 shows an anti-fracking poster displayed alongside a poster for a local toddlers group, and it brings into focus the community concerns over this issue. Now, the easy way of rejecting people's anxiety about this is just to say it is just the NIMBY (not-in-my-back-yard) syndrome; in other words, that folks simply do not like the idea of fracking taking place in their 'back yard'; and they will do anything to oppose it. For me, that is a very lazy way to see the issue. I think it is inappropriate and I do not think it gets us anywhere close to understanding why people genuinely object to it. So, we should dig a little bit deeper.

To do this, I want to get closer to what 'normal' people think about what fracking involves. Figure 10 shows a conversation between two ordinary people in a focus group talking about earthquakes triggered by fracking. One person says, "It's the foundation of the country and if that happens all over the country it'll make it very unstable — talking about the rocks — I have that feeling"; and the other person says, "Well, fracture means break, doesn't it, so obviously you're breaking something." These are people who are trying to understand this process and the idea of the injection brings to mind this pristine world of the subsurface being broken up by the destructive force of fracking.

Another interesting quote is from a mother in a mother and toddler group; she is not an environmental activist, just someone who is confused about the issue of drilling and earthquakes. She said, "It's the drilling that vibrates the earth and causes the earthquakes, and then someone would say, 'Yes, it's ok, it's manageable' — that was recently, but my instinct would say — no, what are you doing? It's not right, it doesn't feel right." Now, for me, there are three elements to this quotation. First, there is the sense that the individual does not understand the technical knowledge, and you could see that in the awkward language — "It's the drilling that vibrates the earth …" I am sure this person would acknowledge that she does not have the technical knowledge. The second element is this 'someone' who says, "Yes it does, it's ok, its' manageable" — presumably an expert, a geologist who has been talking on the radio or television and said something like, "We know about this and we know about the geo-fracture situation, and we know all the geophysics, and said

Kirby Misperton Toddler Group
Mondays 10.30am – 12pm
Kirby Misperton Village Hall
DO YOU WANT FRACKING IN RYEDALE?
FRACK FREE RYEDALE
For more information visit our website:
www.frackfreeryedale.org
NIMBY ?
"Not In My Back Yard." A term for a person who resists unwanted development, such as manufacturing plants, prisons, power companies, or chemical companies in his or her own neighborhood or town.

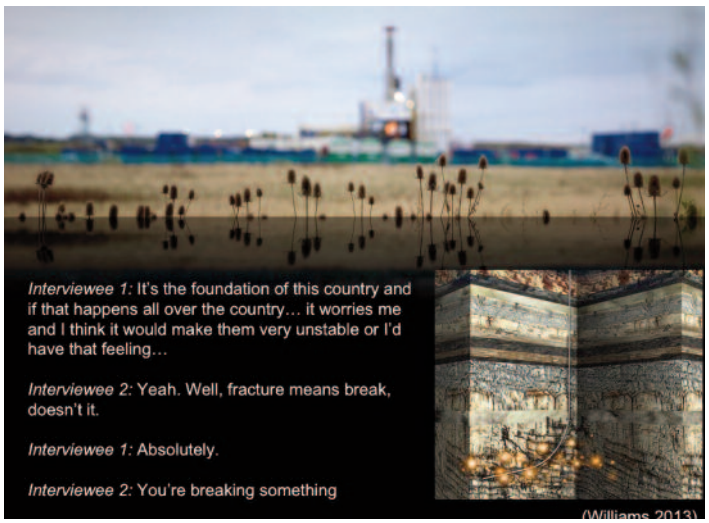
Figure 9 Toddlers welcome — No Fracking!

OK, it's manageable." What is interesting is that you might expect someone who appreciates that she or he does not have the technical understanding of the topic, and who is then confronted with an expert who says it is manageable, might be expected in that situation to say, "Thank you for that — it makes sense now, I'm fine!" But that is not what happens.

What happens is that instinct kicks in instead. The concerned individual says, "It doesn't *feel* right." We all do this when confronted by a topic that we have little or no knowledge about, and feel less comfortable with. Our 'instinct' kicks in. For example, rather than learning, say, the chemistry of quantum physic you would turn to your 'gut feeling'. Here, of course, where we are arguing against instinct in decision-making, how do we scientists influence that? It is completely different to factual knowledge.

Let's consider 'the public' for a moment. For example, think of a crowd walking down Oxford Street in London — 'normal' people. You might wonder how many of them are thinking about the geology of the south-west of England. Probably none. More likely they are thinking about health, or about what to make for dinner, or about shopping. They are unlikely to be thinking about science or about geology. That is because few people think about geology. Not convinced? Think you know lots of people who are interested in geology? Well, I challenge you to go into a Waterstones bookshop and ask to see the geology section.

Figure 10 Focus group conversation about earthquakes and fracking.


Interviewee 1: It's the foundation of this country and if that happens all over the country… it worries me and I think it would make them very unstable or I'd have that feeling…
Interviewee 2: Yeah. Well, fracture means break, doesn't it.
Interviewee 1: Absolutely.
Interviewee 2: You're breaking something
(Williams 2013)

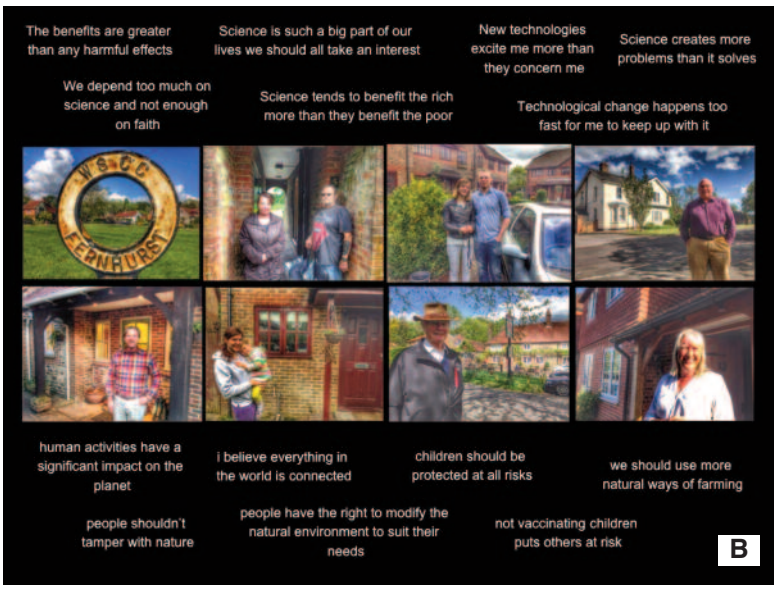

The benefits are greater than any harmful effects
Science is such a big part of our lives we should all take an interest
New technologies excite me more than they concern me
Science creates more problems than it solves
We depend too much on science and not enough on faith
Science tends to benefit the rich more than they benefit the poor
Technological change happens too fast for me to keep up with it
human activities have a significant impact on the planet
i believe everything in the world is connected
children should be protected at all risks
we should use more natural ways of farming
people shouldn't tamper with nature
people have the right to modify the natural environment to suit their needs
not vaccinating children puts others at risk
B

Figure 11 How the public views science — what group are you *in?*

More than likely the shop assistant will give you a blank look — archaeology? theology? Try just asking for science. There will be a kind of quizzical look, and then you will be taken to the back of the shop, to a section of shelves low down that has a label such as 'New Age Crystals'; and there you will find a couple of books about geology. The high-street bookshops pretty much tell you what people are interested in. There is normally a whole wall of fiction, of course, but when it comes to factual topics, most people are interested in history — there are whole sections on just war and military history — architecture, art, cooking, sport, music, travel — but not science.

This situation is not new. Scientists have been doing surveys on science literacy for decades, asking how knowledgeable people are about science, and one intriguing result is that knowledge levels have not changed over that period. So even in the 1960s, amid the 'white heat' of technological innovation, the moon landings etc, the actual level of scientific understanding was not much different than it is now. In fact, a survey done not long after the moon landings revealed that two-thirds of American adults still did not know if the Moon was bigger or smaller than Earth. Clearly there is an intellectual disconnect with science. People may be interested in it, but they do not learn it and retain it for very long, which is a real problem.

Of course, there are lots of different ways of studying the public. One example is a study published in 2014 by the CSIRO — the Australian research organisation. It is a study that confirms many other studies, but is especially punchy. The first thing this study recognises is that there are many different levels of interest in science. It basically divides the public into segments of attitudes towards science — into multiple of slices of the public if you like. The names of the groups are 'Australian-sounding' and the percentages in each group are approximate, but the categories are generally valid. The outcome of the study indicates that about 23% of the public correspond to 'Science Fan Boys and Girls', a group that is especially those close to science. Members of this group probably studied science at school, and perhaps even at university. They are comfortable with science; they watch science documentaries; they might read *Scientific American* or *New Scientist* and they are comfortable having some sort of general conversation about science (Fig. 11).

A second group is called 'Mr and Mrs Average'. Members of this group are a bit more distant from science, although they are still positive towards science. They probably watch some science documentaries, but they probably would not read *Scientific American*; and if they were in a conversation about science they would start to realise that maybe their science was not as good as it used to be. The third group is called 'I wish I could understand it'. It is a small group but the one that has the strongest science appetite; these are people who go to science festivals and science centres most commonly, but what they find is that they cannot understand what they find there. They do not understand the way science is being portrayed to them. Although they are typically older, and a bit more distant from science, they are keen to learn and know about it.

In contrast you have a group that says they are not interested in science because they are interested in other things, for example, politics, music, and other things. Whatever it is, those in this 'Too many issues' group just do not have time for science. Another contrasting group is one that declares, "Actually I hate science. Really, really hate it. When I was at school we had a chemistry teacher who was horrible and she scared me and it was horrible. I don't watch any science documentaries and the kids can't understand why I come out in a cold sweat [when science is mentioned]." Finally, there is an interesting, small group whose members say, "I know all I need to know. I don't need to learn anything more about science because I know all I need to know." These are a kind of people with a different belief system — perhaps a religious belief or a belief in pseudo-science. To these people science is not seen as a relevant way to understand the world.

You probably wonder which group you are in. As OU science graduates or current students, my guess would be mainly 'Science Fan Boys and Girls'; or 'Mr and Mrs Average'; perhaps a few 'I wish I could understand it[s]'? I doubt that any of you reading this article are in any of the 'contrasting' groups.

But the point is, if I am communicating geology, to whom should I communicate? You cannot reach everyone, and the more targeted you are the more effective you can make the message. So, among these groups, these multiple publics, where should I aim my radio and TV programmes? I think that it is probably reasonable to for target BBC2 science programmes somewhere in the middle — the 'Mr and Mrs Average' and the 'I don't understand' groups are safe territory. But then, trying to reach out to the 'Too many issues' and the 'I don't like science' groups might convert some of them. The 'I know all I need to know' group is

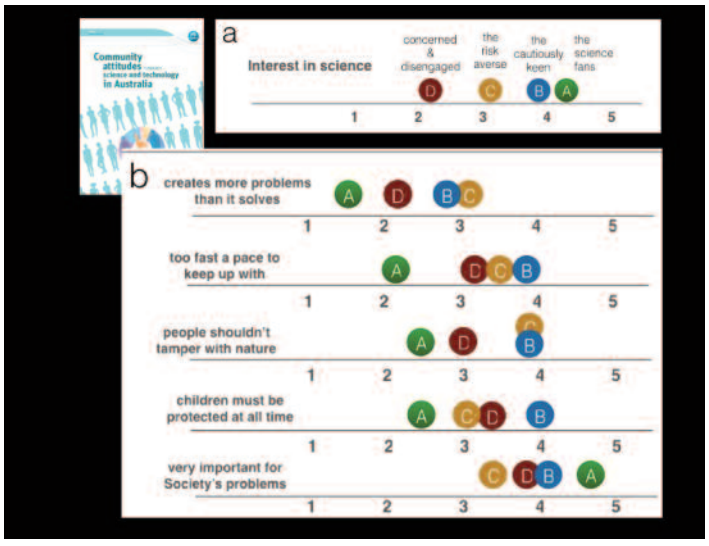
probably not worth trying to reach, as they are unlikely to be worth it; they are unlikely to respond.

The irony is that the group for which it is not worth designing the programmes is the 'Science Fan Boys and Girls'. Why? Because these people will watch such programmes anyway; because they are already interested and will search for and watch such programmes. These 'facts' explain some things; they explain why the music in these programmes is too loud. I am often told, "I don't need thumping rock music to enjoy it." and you are absolutely right, *you* don't — but these other groups do! 'Science Fan Boys and Girls' say that they do not need to be told what they have learned, and what they are going to learn next — but members in these other groups do! So, unfortunately, 'Science Fan Boys and Girls' are the casualties. They will hunt down these programmes because they are interested, and basically, as long as we do not completely mess them up, will watch them.

Now, if the show is for BBC1 — like the programmes scientists such as Brian Cox does — he has to try to reach all the way across the full spectrum of groups. He has to really streamline the science message to try and reach and engage everyone. Alternatively, if the programme is for BBC4 — for example like those presented by Richard Fortey — then you can focus on just your core pro-science groups. So it is all about which target audience you are after. However, a main reason to describe these groups is to highlight that there is a large group of people who are disengaged from science; and if I am trying to communicate to people about geology in general and about the subsurface in particular, there are probably a lot of them in these disinterested and disengaged categories, *and it is important to try to reach them*.

The Australian study also looked at the fundamental beliefs and values that underpin people's judgement of science and technology. By asking how they responded to basic ethical issues, such as, "People shouldn't tamper with nature", or "I believe everything's connected", or "Science tends to benefit the rich more than the poor", the researchers identified four 'values groups'. They are similar to and overlap with the 'attitude groups' described above. The most pro-science group, the 'Science Fans', comprises those who are comfortable with science as being a positive force and do not think that it moves too fast or is bad for society. A group labelled 'Cautiously Keen' include those who are supportive of science but are also anxious about some aspects of it. A less supportive group, called the 'Risk Averse', are those who tend to be conservative in outlook and concerned that science and technology is always changing things. Finally, there is the 'Concerned and Disengaged' group, comprising those who either do not like science at all, or who place their values in other concerns.

Figure 12 Public group responces to value questions about science.



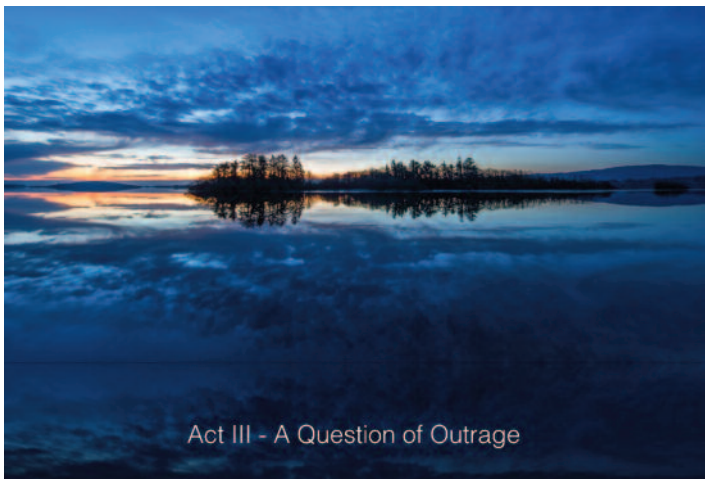
The diagrams in Figure 12 show these different groups arranged according to their responses to different value question. The 'Science Fans', plotted in green (and perhaps including most readers of this article) show something interesting — science fans lie on the extremes of each range, which indicates either highest or lowest. But more than that, science fans are disconnected from the other groups; science fans do not overlap with any of the other value groups. This indicates is that their value systems — as people who are comfortable with science — are not necessarily shared by most other people. And that presents an interesting paradox: we 'Science Fans' feel that we are in the best position to make value judgments about complex scientific issues, while at the same time we may well be in the minority in terms of our how we judge science compared to how members of the other groups judge science.

These two Australian studies reached several conclusions. First, when information is complex, people make judgements based on their personal values and beliefs. Think again of the mother and toddler: she is confused about the technical aspects of fracking, but has far more confidence in her own instincts than in some expert whom she does not know. Second, having made their decision based on their attitudes and beliefs, people then seek to affirm those beliefs. In other words, they deliberately seek out information from other people who will reassure them that they are correct. These days, people go to the Internet and search until they find something that confirms what they think — and in the process they ignore anything that conflicts with their views. Third, people most trust those whose values match their own. So, if scientists have values that are obviously different from their own and from other people whose values match theirs, then they simply do not trust scientists and hence conclude that our views do not count. Fourth, those who reach their attitudes about science based on their beliefs and instincts, rather than forming them from logical facts, are not influenced by logical or factual arguments. In other words, if a person has made his or her decision based on instinct, it is pointless to try to counter that with logical facts.

This point seems to me to be fundamental. As scientists we are trained to use facts and logical arguments. So when trying to communicate with people, facts and logical arguments are what we naturally use.

Science communication & 'public outrage'

The Australian study's over-riding conclusion is that public concerns about contentious subjects are almost never about science, and scientific information therefore does little to influence those concerns. And I think this is a crucial element of science communication. It implies that everything we scientists are trained to do at university is of little help in trying to communicate to those 'other public groups'. So, this idea of educating the public with facts seems pointless because fact and logical argument are not the bases of their decision-making in the first place.



So, what happens when we scientists try to take our science into communities. In the words of Michael Crothers, head of Shell in Ireland, commenting on the reasons for £17million overspend Corrib gas project: "We underestimated the level of community concern and unrest … Inadequate engagement led to decisions that, in hindsight, were too legalistic in approach rather than really understanding what the concerns were, and in spending some extra time working those through… We didn't have what we might have called social licence." What Crothers is expressing here is that if you want to have the community on your side, you have to do it genuinely and you have to have community acceptance to do what you want to do. The problem is that too often in these projects this attempt at community buy-in happens in a legalistic and mechanical way.

There is an extensive social science literature on community responses to environmental risk, and the risk communicator Peter Sandman argues there are two sides to any risk, regardless of whether it is MMR or GM or fracking. The first side is that people overestimate the hazard involved — an ordinary non-specialist person will tend to anticipate a higher hazard than a specialist does, who has gone through all the technical assessments. The second side is that people are angry — outraged even. Sandman argues that while the public often misrepresent hazard, the technical experts often misperceive the outrage. The technical experts claim that the public overestimate or misperception has nothing to do with them. To Sandman the overarching problem is that the public care too little about the hazard and the experts care too little about the outrage. Once again we have this basic 'decoupling', where the experts are looking one way and the public are looking the other way; each group is talking about different sets of facts and having different sets of arguments.

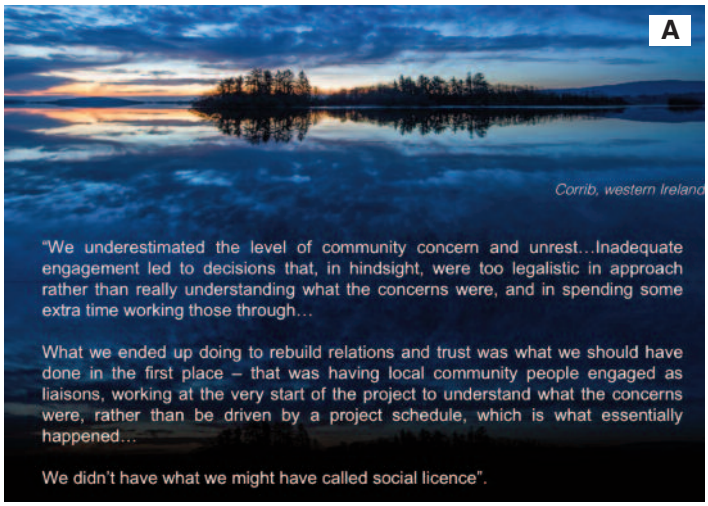
Figure 13 shows people in Balcombe in the summer of 2014 — people upset by the whole prospect of fracking; people angry because they have overestimated the hazards of fracking. Well, that is fairly simple to counter — the geoscientist just needs to explain it better, to explain about the size of the earthquakes, explain what the chemicals are, explain what happens at depth and so on. However, as you might imagine, a straightforward explanation tends to be a relatively rare occurrence. More often, people have overestimated the hazard because they are angry about the idea of fracking, about some aspect of it, so they read up more and 'discover' further reasons to get even angrier. So by this time (the time when the photograph was taken), simply explaining the basic science does not help to remove the original anger. By this time the question is, "Why are they angry?" At this point I can imagine the professional geologist complaining. "Oh that's not my job! I'm not a counsellor, I'm not a sociologist, I'm a technical person — that's not my role!" And of course, in a sense, that is correct. But if your job is to go into that community and communicate on behalf of a technical project, then it is your job to think about why so many members of the community are upset.

Why are they angry? Sandman has a list. Most reasons are obvious: they think the project is being forced on them, that it is not voluntary; it is a matter of whether they think something forced on them is industrial or natural, exotic or memorable. To them fracking — in other words, humans triggering earthquakes — is memorable and exotic. Another issue is whether the consequences might be dreaded or catastrophic rather than non-dreaded and non-catastrophic. Another is whether the perceived hazard is uncertain or even unknowable. These angry people are concerned about whether fracking is controlled by others or controlled by the individuals of the community themselves. They want ot know if the exposure to the threat fair — whether it is spread equally across the community, region or country, or falling on just a few. And they question whether the sources — the companies and people giving them hazard information — are trustworthy or not. Sandman found that one way people gauged degrees of trust was whether experts were responsive or non-responsive to people's concerns. Did the company address or ignore their worries, no matter how ridiculous they seemed (e.g. could molten magma erup out the geothermal borehole?).

These are the elements that define the level of outrage; levels that go up and down across a community, varying by sub-group in a community, and even by individuals (Fig 14). The key point that Sandman makes is that in these situations our job as the experts, as professionals, is to decrease the level of general outrage. We can do that by addressing and lowering these different areas of concern. Some of them we can do little about. For example, many or the technical issues will remain fundamentally uncertain. But we we can influence other issues — especially addressing those areas about whether we are trusted, are responsible, and about how much control we give communities.

Figure 13 Public opinions in Balcombe about fracking.

When information is complex, people make decisions based on their values and beliefs
People seek affirmation of their attitudes (or beliefs), no matter how fringe. They will reject any information that are counter to their attitudes
People most trust those whose values mirror their own.
Attitudes that are not formed by logic (nor facts) are not influenced by logical (nor factual arguments)
Public concerns about contentious science or technologies are almost never about the science - and scientific information therefore does little to influence these concerns.


A
Corrib, western Ireland
"We underestimated the level of community concern and unrest…Inadequate engagement led to decisions that, in hindsight, were too legalistic in approach rather than really understanding what the concerns were, and in spending some extra time working those through…
What we ended up doing to rebuild relations and trust was what we should have done in the first place – that was having local community people engaged as liaisons, working at the very start of the project to understand what the concerns were, rather than be driven by a project schedule, which is what essentially happened…
We didn't have what we might have called social licence".

B
SAVE OUR WATER
NO FRACKING
2 elements in a typical risk controversy…
1. People over-estimate the hazard
2. People are outraged
'The public often misrepresent the hazard. The experts often misperceive the outrage. But the overarching problem is that the public cares too little about the hazard, and the experts care too little about the outrage.'
(Sandman 1993)

Figure 14 Underestimating public anger and outrage.

This means that for those geoscientists going into the communities, most of the critical issues are not likely to be the intrinsically geotechnical issues, and probably not concerns that are geological or scientific at all.

Conclusion

Consider this final thought (Fig 15). Sandman defines 'risk' not as the conventional product of 'hazard' and 'vulnerability', but as the hazard (its frequency and magnitude) multiplied by 'outrage'. It is usually difficult to do much about reducing the hazard element. But we as scientists can often actually do something about how angry people are. This is one of the aspects we need to work on.

In conclusion, there are two things that as geoscientists we need to get better (Fig 16). First, we need to talk better, we need to explain things better — for example in the Balcombe case we need to explain the hazard more clearly, and to explain more precisely the context within which we are working. But the harder task is that we need to learn to listen better, to hear what worries people. In other words, the experts need to listen to the non-experts more, even though the latter actually know very little about it. That paradox is a real problem. As long as we deal with issues that are ethically and morally questionable, and that require a public mandate, we have to acknowledge and somehow build in that public ignorance, that sense of not knowing. We need to engage the public in conversations and try genuinely to find out what they are worried about. From that, we can re-cast our technical messages in ways that get across to them the information that people actually need and want.

That is the big challenge that I see in geoscience communication. It is not just talking about it, but listening to replies about it.

You have been very good listeners — thank you.

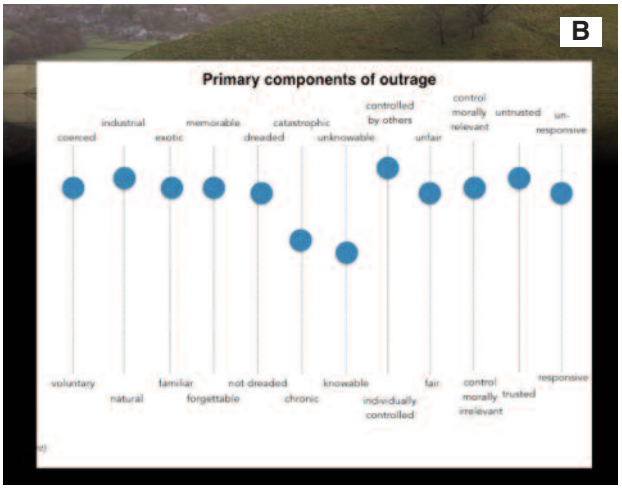


Figure 15 Sandman's 'risk list' — hazard multiplied by outrage.

So, scientists face 2 communication challenges:
1. to talk better - to explain that the hazard is low
2. to listen better - to hear that the outrage is high
RISK = HAZARD x OUTRAGE

Figure 16 Two things that as geoscientists we need to get better.

Book Review

Lyle, Paul 2016 *The Abyss of Time: A Study in Geological Time and Earth History*. Edinburgh: Dunedin Academic Press Ltd (ISBN hardback 978-1-78046-039-0, ePub 978-1-78046-543-2, Kindle 978-1-78046-544-9; 204pp; hardback £24.99)

The author is a retired Geology lecturer at Ulster University who has written this book to bring a geologist's appreciation of time to a wider audience.

Paul Lyle combines two contrasting aspects of time: "Time's arrow", where events occur in a unique sequence of events and "Time's cycle", where processes occur in a recognisable and repeatable cycle, such as uplift, erosion and sedimentation.

He considers the history of the human relationship with seasons and time; and how the passage of time has been marked and measured by *Homo sapiens* since Palaeolithic times on a scale relevant to the human life-span, but that geological time required a shift of thinking.

Lyle discusses the differing time-scales of exploitation of physical resources against the time taken to form them. He looks at the history of how philosophers and scientists have addressed the idea of the age of the Earth and tried to calculate a figure. He looks at the history and development of major geological theories.

The idea of relative time and stratigraphy is discussed using good and clear exemplars based on rubbish from old mining camps (tin cans, beer bottles and nails) to illustrate the idea of relative time on a human scale before expanding the idea into 'deep time' with the use of fossils. He explains how the stratigraphic column was developed and has been refined.

From here the author leads into the development of absolute time and the search for the age of the Earth, with a brief discussion of supernovas and the development of our solar system to the use of radiometric dating to calibrate the stratigraphic column and to investigate the Precambrian. The same techniques are then used to consider human archaeology, tephrochronology, and how the two can be combined to provide a dating framework. Correlation and detail can be added by considering growth rings in shells and trees, radiocarbon dating and magnetochronology.

Lyle ends with a look into the future…

I enjoyed this book and found the way he pulled different threads together very interesting and informative. I would recommend this book to everyone, whether a geologist or not.

— Helen Coombs, BSc Hons Geosciences (Open)

Book review

Richards, Jim 2016 *Gold Rush*. September Publishing (ISBN 978-1-91046-336-9; paperback, 364pp; £10.99)

His childhood fascination with the gold artefacts in the local museum led Jim Richards into voluntary work as a tour guide in the ancient Roman gold mines at Dolaucothi, West Wales and to try gold panning in the River Cothi. This encouraged him to study geology at Goldsmiths College, followed by recruitment to the Parachute Regiment, training at Sandhurst and military service in Northern Ireland. He resigned his commission and cashed in his pension to join the Brazilian gold rush. He hitched a flight to Belize, then crossed into Guatemala, to Antigua, where he spent some months learning Spanish. On arrival in Georgetown, Guyana, a chance encounter brought him to Golden Star Resources' headquarters where he was offered a job managing a mining team in the outback; here his Sandhurst training proved invaluable in improving the living conditions of the mining team.

Golden Star mined alluvial gold and diamonds; Jim gained knowledge and experience until he felt able to begin prospecting on his own account. After several years of artisanal gold and diamond recovery, by dangerous, underwater dredging operations, he made a trip to the gold boom district of Boa Vista, Brazil. Not liking what he saw there, he returned first to Guyana then home to the UK to recover his health. Not enjoying unemployment or the British weather he decided to try Australia next.

He was taken on by St Barbara Mines as an exploration geologist at Meekatharra open-cast gold mine in Western Australia, where he discovered a high-grade gold vein. At this point he realised that controlling a mining company was more profitable than diving for diamonds in Guyana or prospecting for an employer in Australia. After exploring for gold in Laos and Indonesia, he returned to Australia. While working in the oil industry he purchased the mineral rights of a diamond area in Western Australia, which he explored during his leave periods. In order to fund his diamond prospecting operations full time, he floated his company, Ozwest, on the stock market. As iron became more valuable he decided to prospect for iron instead, acquiring mineral rights near Pilbara, where he discovered the Railway iron ore field. In 2010 the company was taken over and his fortune was made.

The introduction to each section has a small-scale outline map of the country and a brief description of the geological processes that resulted in the mineral deposits, followed by an account of early exploration and exploitation of the resource. There are some photographs but no diagrams.

— E. A. Williams, BSc Hons (Open)

Devonian-Carboniferous rifting and Variscan plate convergence: south-west England and the closure of the Rheic Ocean*

Dr Robin Shail

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[Unfortunately, Dr Shail was unable to write up his lecture as an article for the OUGS Proceedings*. As up to the time of the printing deadline Dr Shail did not reply to communications about writing up his lecture, and although we provided him with a near-verbatim transcription of his lecture recording, there were many queries in the text and it was not possible to produce an acceptable article from the transcribed text. Therefore, according to our OUGS Symposium lectures policy, it is only possible to publish the abstract he submitted to the OUGS 2016 Exeter Symposium Committee for the Symposium brochure.]*

Abstract

The Rheic Ocean initiated by the earliest Ordovician and had closed by the latest Devonian, resulting in the Variscan orogen and, ultimately, the final assembly of Pangea by the latest Carboniferous. Most plate tectonic reconstructions place the Rheic suture offshore, immediately south of south-west England, where its trace is inferred through the western English Channel and Western Approaches. It represents the last time that British lithosphere formed part of an active convergent margin, but it is incompletely understood, partly as a consequence of its offshore position and its post-Variscan sedimentary cover.

South-west England provides a partial insight, from the northern margin, of the closing stages of the Rheic Ocean. Pre-Devonian basement affinities are poorly constrained and there are no pre-Devonian palaeomagnetic or palaeofaunal data; south-west England may represent the southern margin of Avalonia or a separate peri-Gondwanan terrane. Rifting of continental lithosphere had initiated by the earliest Devonian; then Devonian–Carboniferous successions were deposited in six E–W-trending sedimentary basins that defined the south-facing proximal-passive margin to a short-lived marginal or successor basin to the Rheic Ocean.

Much of the sedimentary and magmatic record in the proximal-passive margin indicates variable-depth marine environments that were controlled by the interplay between rift-related subsidence, by global changes in sea level and by sediment supply. The Staddon Formation (Looe Basin — of Emsian date [*c.* 419–359Ma]) and/or the Hangman Formation (North Devon Basin —Eifelian [*c.* 394–388Ma]) record more substantial clastic inputs from the north that might be a consequence of Acadian deformation. The southward transition to highly attenuated continental lithosphere of the distal passive margin exhumed lithospheric mantle, and a short-lived Middle Devonian oceanic spreading centre is partially recorded in allochthonous units of the Gramscatho Basin and the Lizard Complex ophiolite. Episodic rifting of the proximal-passive margin persisted through the late Devonian and early Mississippian periods.

South-west England occupied a lower plate position during late Devonian Variscan convergence. The Gramscatho Basin primarily records late Devonian syn-convergence sedimentation, including spectacular olistrostomes containing Gondwana-derived Ordovician quartzites. The S–SE-dipping Rheic-Rhenohercynian suture is imaged on seismic lines in the western English Channel and continues 250km WSW through the Western Approaches to the present-day continental margin. The orogenic wedge, comprising the upper plate and frontally accreted elements of the distal passive margin, collided with the continental slope in the earliest Mississippian. Variscan shortening migrated northward through the proximal-passive margin and was accommodated by the thick-skinned inversion of sedimentary basins and pre-rift basement above a mid-crustal décollement. The style of deformation, including the presence of facing confrontations, was strongly influenced by rift-basin geometry. The Culm Basin evolved from a rift basin to a Pennsylvanian thrust-top basin; its infill, derived from the east and then from the north, indicates the influence of uplift caused by frontal thrusting and strike-slip along the Bristol Channel-Bray Fault. 'Docking' with southern Britain resulted in late Pennsylvanian deformation across south-west England and contemporaneous inversion of the Culm and North Devon basins.

* The lecture was delivered by Dr Shail; co-authored by Dr Brian Leveridge, BGS.

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Book review

Jha, Alok 2015 *The Water Book*. London: Headline Publishing Group (ISBN 978-1-47220-953-5; paperback, 376pp; £10)

This is a very mixed book. There are three main strands: an account of a voyage from New Zealand to Antarctica; a description of the physics and chemistry of water; and an account of space exploration and speculation.

1. The voyage: The author travelled as a paying passenger on a research ship — an ice-strengthened Russian vessel. He commences with a detailed account of seasickness! He does not appear to be aware that ice-strengthened ships differ from ice-breakers in that they are not designed to break through the ice with a strong, pointed bow, but to ride up on ice of moderate thickness, crushing it beneath their weight. For this purpose they are round-bottomed and consequently roll horribly in the Southern Ocean. (I travelled south on one while working with the Australian National Antarctic Research Expeditions (ANARE), and, unlike the author, also travelled back to Australia in the same way). The end of the story shows that unanticipated risks haven't changed since Shackleton's day, but the options for rescue certainly have.

2. Water physics and chemistry: The author is a science writer, which would appear to mean a journalist who specialises in writing about scientific subjects. As such, the book is obviously aimed at non-scientists, despite going into considerable detail at the molecular level.

I volunteered to review the book as I have long been looking for an update to the book I read long ago entitled Water (author's name forgotten, but a scientist*), and covering what was then known of its physics, chemistry and biology. This is certainly not the book I have been hoping for. I did learn some new facts, but also noticed occasional factual errors in information learned in OU courses, so cannot be sure of the correctness of all of Alok's text.

3. Space exploration and speculation: While the accounts of space exploration were quite interesting, I got more than fed up with all the speculation as to where life might be found and of what nature it might be.

So, is this book worth reading? Probably not for anyone who has studied some recent physics, chemistry and biology (there wasn't much geology). Perhaps for someone with no scientific background. I'll be returning the book to the OUGS Archivist, Jane Michael, in due course should anyone want to give it a try.

** I keep a list of all books I read, but, in pre-computer days, this was in a small loose-leaf file, which was stolen in New Guinea, together with much else. But the loss of this booklet alone is enduring, as it also included my lists of all species seen and my address book).*
*** The book should be available at AGM 2017 — Ed.].*

— Zoë Gardner, BA/BSc Hons (Open)

Book review

Shonting, David, and Ezrailson, Cathy 2017 *Chicxulub: The Impact and Tsunami*. Springer Praxis Books (ISBN 978-3-31939-485-5; hardback, 121pp; £17.99)

The aim of this book is to tell the tale of the asteroid that made the Chicxulub crater and is credited with the extinction of the dinosaurs "as a narrative, based on science for the general reader". It has been written by a physical oceanographer and a teacher who have drawn together information from a wide range of disciplines to tell their version of the events.

The book starts with an imagining of the event from a vantage point on a mountain in Cuba. It describes the asteroid's appearance in the night sky, its entry into the atmosphere and the devastating effects of its plunge into the shallow sea of the evolving Gulf of Mexico. The book then explores the science and history of the story in five chapters:

• 'The Orbiting Objects' explains asteroids, associated energies and gives examples of craters visible today and observed meteorite events explaining the science involved as required.
• In 'The Tale of Chicxulub' we learn the history of the Alvarez discovery and the collection of the evidence to support their theory.
• 'A Scenario for the Chicxulub Impact and Energies' gives the geological setting of the event and descriptions of different components associated with the explosion and ejecta dispersal.
• 'The Chicxulub Tsunami' describes tsunami wave generation and wave physics, and gives recent examples. It then explores the possible extent and effects of the wave.
• The last chapter, 'Long Term Global Effects', explores the possible result of the asteroid impact and its effect on the world of the dinosaurs.

Did this book achieve its aim? The authors cover all the main topics and use some good examples of associated phenomena along with a range of everyday analogies. I did learn some new things, but had to struggle through the text, as the language style was poor. The authors use a chatty, jokey style in parts and there are too many editing and proof reading errors. They also follow some scientific writing conventions (using an abstract to start each chapter) instead of using a straight narrative style. The illustrations are of a variable quality with some of the black and white images barely understandable.

This was a disappointment, as the publisher has a history of producing good science works. The Open University has taught me the benefit of a precise and concise style to my writing and I now look for that in all that I read.

— Averil Leaver, BSc Hons Geoscience (Open)

Early post-Variscan tectonics and magmatism: south-west England granites and their associated mineralisation

Dr Robin Shail

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(R.K.Shail@ex.ac.uk)

[Unfortunately, Dr Shail was unable to write up his lecture as an article for the OUGS Proceedings*. As up to the time of the printing deadline Dr Shail did not reply to communications about writing up his lecture, and although we provided him with a near-verbatim transcription of his lecture recording, there were many queries in the text and it was not possible to produce an acceptable article from the transcribed text. Therefore, according to our OUGS Symposium lectures policy, it is only possible to publish the abstract he submitted to the OUGS 2016 Exeter Symposium Committee for the Symposium brochure.]*

Abstract

Variscan convergence ceased in the latest Carboniferous and was replaced by a NNW–SSE extensional regime that persisted throughout most of the Early Permian. The onshore expression of early post-convergence deformation includes widely developed shear zones and detachment faults that demonstrate the extensional reactivation of Variscan thrust faults with their 'top' to the south-south-east. There is a progression to higher-angle, brittle extensional faults during exhumation that cut out earlier structures. Offshore, reactivation of the Rheic-Rhenohercynian suture zone was accompanied by the development of the upper plate Western Approaches basins that locally include substantial volcanic infills.

The granites in south-west England were generated and emplaced over a period of >20Ma (*c.* 293–270Ma) as a consequence of this extensional regime. Lithospheric thickening and thinning controlled the thermal evolution of the lithosphere and the generation of enormous melt volumes. While predominantly sourced from the crust, there is a minor direct contribution from the mantle-derived melts that were responsible for substantial heat input into the lower and middle crust. The Cornubian Batholith reflects melting in the exhuming lower plate of the Rhenohercynian/Rheic suture while the Haig Fras Batholith, located 100km north-west of the Isles of Scilly, reflects melting in the exhuming lower plate of the Bristol Channel Fault Zone. Both batholiths are located above their source zones.

The dimensions of the Cornubian Batholith are reasonably constrained but it is probably thinner (6–8km) in many locations than implied by most gravity interpretations. At least 40,000km^3 of magma was generated and emplaced during the Early Permian. Relations with host rocks are consistent with progressive emplacement of melt batches by roof-lifting and, possibly also floor-depression, which resulted in markedly composite plutons comprising sheet-like bodies at a variety of scales.

The earliest stages of batholith construction, recorded in the older Scilly, Carnmenellis and Bodmin Moor plutons, indicate localised solid-state fabrics and ductile shear zones compatible with a top-sense of SSE shear, and hence coupling with extensional reactivation of host-rock thrust faults. The later granites (Land's End, St Austell and Dartmoor) do not exhibit solid-state fabrics. Alkali feldspars are overwhelmingly magmatic rather than metasomatic, but may have protracted crystallisation histories. Magmatic-state fabrics are present in both older and younger granites and are often complex; there is commonly evidence for NNW–SSE stretch of magma during emplacement.

Enclaves represent host-rock or hybridised melts formed by mixing and mingling with mantle-derived melts, and there is some restite. Muscovite-dominated source melting generated early magmas; biotite-dominated source melting generated later magmas. Biotite and tourmaline granites appear cogenetic, but the topaz granites probably represent distinct source-melting events. Rhyolite-microgranite ('elvan)' dykes correspond to the range of pluton compositions and, at least locally, had an eruptive expression.

Regional tectonic deformation generally resulted in steeply dipping fracture networks, both within both the granites and within their host rocks, before and during the construction of the Cornubian Batholith. These controlled world-class magmatic-hydrothermal W-Sn-Cu-As-Zn-Pb mineralisation. Mineralisation is related to magmatic/tectonic episodes rather than to long-lived granite-induced convective hydrothermal circulation. Fault-controlled flow of fluids from crystallising magmas and variable mixing with meteoric and, to a lesser extent, metamorphic and basinal fluids resulted in the major lode systems. Changes in stress regime resulted in variable vein/lode orientations across the province, particularly those associated with the youngest granites. Selective reactivation of fault systems was commonplace, both during the Early to mid-Permian and during subsequent Mesozoic and Cenozoic tectonic episodes.

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Book review

Park, Graham 2015 *Introducing Natural Resources.* Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-048-2; paperback, 117pp; £14.99)

This relatively slim book is part of a series produced by Dunedin covering aspects of Earth Science. Books in the series include *Introducing Geology* (also by this author), *Mineralogy,* and similar subjects.

The book is aimed at "those, whose interest in natural resources has been stimulated perhaps by media coverage of declining resources or environmental pollution and who want to better understand the issues involved". Its somewhat superficial nature means that any serious student would have little need for this book, but it is well written and interesting nonetheless.

The book has three main parts; the first covers the origin and early history of the Earth. This is followed by two geology-orientated chapters, describing how mineral resources are redistributed and concentrated in various settings. This is the most technical part of the book and some geological knowledge would be useful.

The second main part of the book is on much safer ground. It describes the periodic table, starting with the transition and post-transitional metals, then continues with the alkali and alkali earth metals, and ends with the non-metallic elements.

Each example is described in the same manner; first, a brief description of the element with its chemical symbol and atomic number. Then a history of its use, followed by the occurrence and host minerals of the element, and finally current production volumes (there are numerous tables showing major producing countries, although years vary) and what remaining resources may be.

Although repetitive in format, this part of the book is interesting and could act as a handy *aide-memoir* rather than having to drag a big book down from the shelf.

The last part of the book is devoted to energy resources, both renewable and non-renewable. The author discusses the origin and uses of coal, oil, natural gas, biogas and gas hydrates, and nuclear power. Graham outlines the environmental concerns associated with the consumption of fossil fuels such as pollution, contamination and the production of greenhouses gases. Renewable energies are discussed, including biomass, solar, geothermal, wind and hydro energy.

The book finishes with a summary of the challenges facing the planet in providing energy for the future without irreparably damaging it.

Overall, this book is informative and nicely illustrated but, by its nature, can only act as a guide for further research. A selected reading list is included.

— Nigel Combley, BSc Hons Geosciences (Open), FGS

Book review

Smellie, John L., and Edwards, Benjamin R. 2016 *Glaciovolcanism on Earth and Mars: Products, Processes and Palaeoenvironmental Significance.* Cambridge University Press (ISBN 978-1-107-03739-7; hardback, 483pp; £89.99)

Glaciovolcanism describes "the interactions between magma and ice in all its forms, including snow, firn, ice and any meltwater produced." The study of glaciovolcanism is of some importance: in particular it helps us to understand and manage the hazards associated with volcano-ice interaction and it can provide important palaeoenvironmental information on past ice sheet characteristics. Our understanding of glaciovolcanism has grown rapidly over the last 20 years or so, but is widely dispersed in the research literature. This book reviews much of this development and thus provides a comprehensive overview of the current state of glaciovolcanism.

The distribution of glaciovolcanism on Earth and a review of observations of historical and recent glaciovolcanic eruptions provide an excellent introduction. The next four chapters tackle the chemical and physical properties of ice and magma together with the physics of magma-ice interaction. The following four chapters then concentrate on the products of glaciovolcanism, both the distinctive landforms and the characteristic sequences of glaciovolcanic rocks. Both authors have extensive field experience and these chapters provide much useful detail. The final chapters take a wider viewpoint by considering glaciovolcanic sequences as palaeoenvironmental proxies, glacier-volcano interaction, glaciovolcanic hazards, Martian glaciovolcanism. The book concludes with a review of outstanding areas for research.

This book has been well produced and proof read. Line drawings are clear and informative. Photographs are mostly black and white, although a small selection is reproduced in a colour plates section. On occasions I found it difficult to pick out features on the black and white photographs and I would have preferred more colour photographs. This would, no doubt, have added to the cost of a book that is already quite expensive.

All earth scientists would enjoy a dip into this book. For those contemplating serious study or research in glaciovolcanism, the book should be studied from cover to cover — it will become the standard reference text for glaciovolcanism for the next few years at least.

— Duncan Woodcock, BSc Hons (Open), PhD, and continuing ES student

Red rocks and volcanoes — the Permian of Devon

Dr Richard Scrivener and Dr Sarita McVicar Wright

[Unfortunately, Dr Scrivener and Dr McVicar Wright were unable to write up their lecture as an article for the OUGS Proceedings. *As up to the time of the printing deadline neither replied to communications about writing up their lecture, and although we provided them with a near-verbatim transcription of their lecture recording, there were many queries in the text and it was not possible to produce an acceptable article from the transcribed text. Therefore, according to our OUGS Symposium lectures policy, it is only possible to publish the abstract Dr Scrivener submitted to the OUGS 2016 Exeter Symposium Committee for the Symposium brochure.]*

Abstract

The Permian succession of Devon includes up to 1000m thickness of continental red beds, mostly sedimentary breccias and sandstone. These rocks are exposed along the coast from Torbay and northward to the Exe Estuary, and also have substantial outcrops in the Exeter area and in the Crediton Trough, a half graben extending from Hatherleigh in West Devon eastward to the Exe Valley. In the lower part of the Permian succession there are local developments of basic igneous rocks, including alkali basalts, trachytes and lamprophyres, known as the Exeter Volcanic Rocks. Throughout the succession there is evidence of contemporaneous felsic igneous activity, mostly as clasts in the sedimentary breccias. [The lecture by Dr Scrivener and Dr McVicar Wright described and examined these Permian rocks and discussed their origin and chronology. They considered new evidence for the age of the lower part of the red beds and also for the Permian-Triassic boundary.]

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Book review

King, C. (ed), Gale, A. S., and Barry, T. L. 2016 *A Revised Correlation of Tertiary Rocks in the British Isles and Adjacent* Areas of NW Europe. London: The Geological Society (ISBN 978-1-86239-728-6; paperback, 719pp; £120 (Fellows £60)

This book is a fitting tribute to the work of the late Dr Chris King, who was instrumental in the research and preparation of the manuscript, using more than 40 years of papers and data. The references section alone covers more than 50 pages.

The study of Tertiary rocks has increased rapidly over the past 50 years with the discovery of oil and gas deposits, initially in the North Sea Basin. Commercial interests recognised the need for accurate survey, and delineation of potential reserves and seismically-based sequence stratigraphy has become widely developed, albeit not to internationally agreed disciplines.

Biostratigraphy also plays an important part in interpreting the geological record and the incidence of fossils related to chronostratigraphy is well explained. Other methods of dating Tertiary rocks are magnetostratigraphy, oxygen and carbon isotope analysis, analysis of heavy mineral and tephra deposits, and radiometric dating.

Bringing together such a huge amount of data — much of which is sparse, missing, contradictory or outdated — is a gargantuan task. Taking into account that the book also covers UK and North-Western European landforms, as well as Paleogene igneous rocks, the true scope of the project is evident.

A large part of the book looks at the North Sea Basin. It starts with an overview showing its geographical extent. The varying names given to different Groups and Formations by each country have been standardised, albeit arbitrarily.

This is followed by extremely detailed analyses of the geology from Early Paleocene (Danian) through to Early Pleistocene. These pages have many figures showing successions in stratigraphic detail. Each Formation or Member (and even down to units in many cases) are described in terms of their lithology, distribution and relationships, biostratigraphy, depositional environment and age. Reference is also made to the wells providing samples, where available.

A similar approach is also taken when describing the onshore East Anglia and London, Hampshire and Dieppe basins. After a short chapter on non-marine sediments, the book takes us west to the Western Approaches, the Celtic Basin and as far afield as Greenland.

The book finishes with Tertiary igneous rocks of Western Scotland, Northern Ireland and the north of England, and an excellent appendix.

The writers stress that this is not a textbook on the Tertiary geological history of this area, but a critical summary of current knowledge; it is a must for anyone who works in, or is seriously interested in this field.

— Nigel Combley, BSc Hons Geosciences (Open), FGS

Book review

Roycroft, Patrick 2015 *648 Billion Sunrises: A Geological Miscellany of Ireland*. Dublin: Orpen Press (ISBN 978-1-90989-568-3; paperback, 194pp; €16.99/£18.72 [also available for £13.50 from Amazon UK])

Some readers of this review will have met Dr Patrick Roycroft at the OUGS Ireland Branch visit to the UCD Mineral Collection in November 2016. For those who are less familiar with Patrick, he is a geologist with a PhD from University College Dublin and is currently working on a project to curate and research the aforementioned UCD Mineral Collection with the help of the National Museum of Ireland. He is ex-president of the Irish Geological Association and an editor with the geological journal Elements. He has also been involved with Ingenious Ireland, creators of the excellent Dublin Rocks! audio-guide tour of Dublin, which I recommend.

His book *648 Billion Sunrises: A Geological Miscellany of Ireland* was published in November 2015, and is aimed at the layperson with an interest in geology, but not necessarily in any particular academic studies in the area. At 194 pages it is a general introduction to the geology of Ireland, which covers the broad geological history of the island as well as dispelling some myths — for example that misguided belief held by some that the Sugar Loaf Mountain in Wicklow is an extinct volcano rather than what it really is, primarily composed of quartzite. The book is written in a lighthearted and easy-to-understand way, and is full of anecdotes, which help to make each subject more interesting. Regarding the Sugar Loaf Mountain example, he also explains what exactly a 'sugar loaf' is and why a mountain should be given such a name.

The book is divided into short sections, each self-contained and covering a separate topic, which makes it easy to dip in and out of the book at leisure. As well as focusing on a few of the more famous features of Irish geology, he also conducts a county-by-county geological review of the island, identifying for each a separate county rock, mineral and fossil — a great way to review the geological variety contained in such a small part of the world. Finally, the historical context behind geological findings, the socio-economic impact of local geological resources and the genealogy of the people behind the development of geoscience in Ireland are touched on in the book, making it much more than a general review of Ireland's geology, but also an insight into its history and the role geology has played in Irish society.

The many anecdotes and simple way of explaining concepts and features by such an authoritative scholar make it likely that even someone already familiar with our island's geology will discover something new or learn more about a topic they thought they already understood fully. The book contains the latest geological findings, including unpublished and original research, meaning that it is also an excellent way of keeping up with the latest developments in Irish geology.

Finally, references are provided for anyone interested in looking deeper into any topic touched on in the book. Overall I feel it is an excellent read and an important addition to the library of anyone interested in the geology of Ireland.

— Emmanuel Kavanagh, BSc Hons Natural Sciences (Open)

The Critical West: raw materials and rare earths

Prof. Frances Wall and Camilla Owens

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Abstract

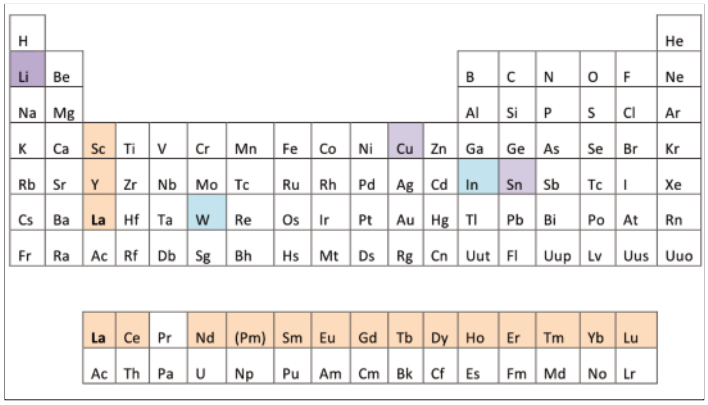
Critical raw materials are defined as raw materials that are economically important but vulnerable to supply disruption. They are important now because we mine and use a wider range of elements than ever before. Digital and medical technologies, clean energy and electric vehicles are examples of applications that use the properties of particular materials. These high-technology applications often only need small amounts of raw material that can come from just a few mines in one or two countrie,s and hence the supply risk. The UK South West has the world's fourth largest deposit of the critical metal, tungsten, being mined at the Drakelands mine in Devon. The South West may also have potential for indium, as well as lithium and tin, which although not defined as 'critical' at the moment are also important high-technology raw materials. The UK Natural Environment Research Council funds a research programme called 'SoS Minerals' that is helping to find secure and environmentally-friendly solutions to critical metals supply for environmental technologies. Rare earth elements (REE) are perhaps the most famous critical metals. They have many use,s but supply is dominated by China. The geochemistry of REE is controlled by the lanthanide contraction, which results in the 15 REE almost always being associated with each other, but undergoing a smooth fractionation of light from heavy members of the series. The SoS RARE project is researching how light and heavy REE are transported and concentrated, including working on carbonatites in Malawi and Namibia, in order to help exploration companies target the REE that are needed the most. There are many different types of REE deposit to choose from and besides working to help make exploration and processing of carbonatites and alkaline rocks more efficient, SoS RARE is working to understand how REE are concentrated in ion-adsorption clay deposits and how they may be extracted in an environmentally friendly way. If this can be achieved, they could provide a low-impact way to produce REE in the future.

Introduction

This article considers the need for raw materials and the relatively new concept of 'critical raw materials', using the rare earth elements (REE) as particular examples. It takes a worldwide view, but will show that there is particular interest in this topic area in south-west England, both in leading research and in critical raw materials of our own in the region.

New technologies use an increasingly wider range of elements in their manufacture. A century ago the main metals used were iron, copper, gold and silver; now it takes 60 different elements to manufacture a modern computer chip (Graedel *et al.* 2015). In the Periodic Table of the elements (Fig. 1) there are some that are easy to recognise as commodities that are mined. For example the first row of the transition metals includes iron, zinc and copper. Aluminium will be familiar and tin is a famous metal in the south-west of England. Most of the other elements also have commercial uses. Some of these are small volume and specialist uses, but nevertheless, particular elements do the job better than any of the others. For example, a coating of indium tin oxide makes all of our touch screens on digital devices work, tantalum is an ingredient of small capacitors in electronics, including mobile phones, and platinum is an essential ingredient of catalytic converters in cars. Geologists now have an opportunity to work on a much more diverse range of these more unusual elements and this has signalled a change for people who are interested in ore deposits.

Figure 1 Periodic Table: brown = Scandium, yttrium and the lanthanides (lanthanoids), which together comprise the rare earth elements (REE); blue = critical metals, tungsten and indium, that occur in Cornwall and Devon; purple = other elements that occur in Cornwall and Devon and are discussed in this article: lithium, tin and copper.


H
He
Li Be
B C N O F Ne
Na Mg
Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Tc I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo
La Ce Pr Nd (Pm) Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

Critical raw materials — rare earth elements

A prime example of the use of specialist metals in digital and green technologies is that of the rare earth elements (REE). These consist, according to the International Union of Pure and Applied Chemistry (IUPAC), of 17 elements: lanthanum (La) to lutetium (Lu) (the lanthanoids) plus yttrium (Y) and also scandium (Sc) (Fig. 1). Scandium actually behaves geologically rather differently to the other REE, so is not considered further here. Promethium (Pm) has no long-lived isotopes and does not exist to any appreciable extent in nature, so this gives a group of 15 elements.

There are many applications of REE (Hatch 2012), including many in close proximity to us all the time. Examples include: direct drive motors in large wind turbines and electric cars, nickel metal hydride batteries in hybrid cars, catalytic converters, catalysts used in petroleum refining, lasers, MRI medical imaging, fluorescence is medicine, cancer therapies, anti-forgery marks on bank notes, self-cleaning ovens, low-energy lighting, and computer hard disk drives, phosphors in computer and TV screens and voice coil motors (speakers) in mobile phones. Most of these uses rely on just one element of the rare earth series and many rely on neodymium (Nd) in the form of neodymium iron boron permanent magnets, which are the strongest permanent magnets made. Most of the applications do not use very much of any of the REE, usually only a few pence worth. The main exception to

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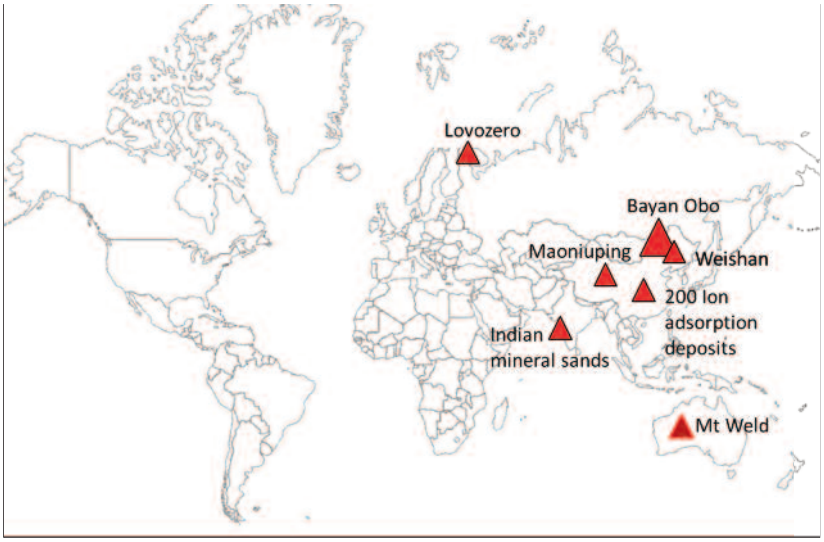


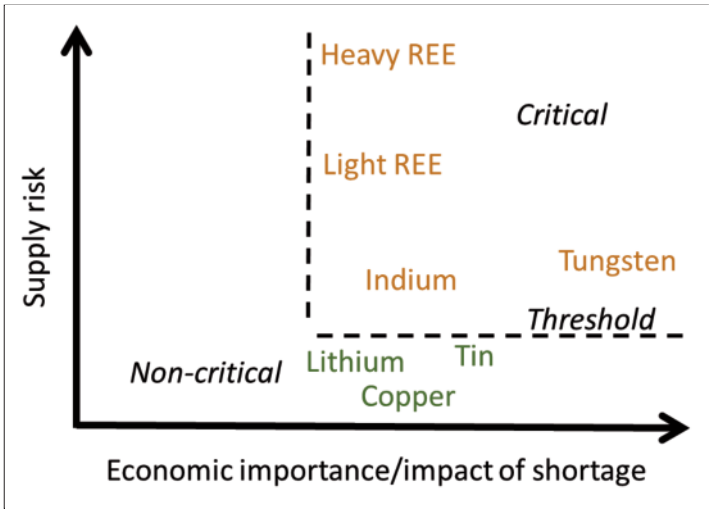
Figure 2 Location of the world's main REE mines. The largest mine, which provides the majority of the light REE, is Bayan Obo, Inner Mongolia, China. Almost all of the world's heavy REE come from ion-adsorption deposits in southern China. There are smaller mines for light REE at Weishan and Maoniuping/Dalucao China. The main REE source outside of China is the carbonatite mine at Mt Weld, Western Australia, which refines its monazite ore in Malaysia. The mineral, loparite, is mined from nepheline syenite rock at Lovozero, Kola Peninsula, Russia as a source of niobium with REE as a by-product. India produces REE from monazite recovered from mineral sands along its coasts.

these very low levels of REE is the amount of REE needed for large, offshore wind turbines. A Siemens D6 wind turbine has blades the size of an A380 airplane and can use half a ton per megawatt of wind turbine power. In most cases, it is not that REE are valuable in terms of money, but that they are essential for functionality. In almost every application, the REE are the only thing that will do the job. Without them, that application — the car motor, the catalyst, the medical application, the smartphone — will not work. They cannot be easily substituted by other materials and that is why they have become so important in our everyday lives. Despite all of their uses, only 126,000 tons of REE where mined worldwide in 2016 (U.S. Geological Survey 2017). For comparison, this figure is over one hundred times *lower* than the 19.4 million tons of copper produced in 2016 (U.S. Geological Survey 2017).

So what is the problem; this all seems like good news, with interesting elements doing wonderful things, and still only needed in small amounts? The problem is that practically all the REE that are mined in the world are coming out just one country, and that country is China. China has the largest mine producing REE and it is no coincidence that they dominate the REE market. There is a plaque in Baotou, Inner Mongolia, China with words by the former Chinese premier, Deng Xiaoping, in 1992, "There is oil in the Middle East, there is rare earth in China". As China produced REE from the world's largest mine at Bayan Obo in Inner Mongolia, the rest of world was content to buy the resulting REE products at conveniently low prices. China established dominance over the whole REE manufacturing supply chain. Life went on as normal elsewhere, until in 2010 China reduced export quotas of REE by 40% and prices rose dramatically. In 2011 there was a diplomatic incident in the South China Sea when a Japanese patrol boat collided with a Chinese trawler (Hatch 2012) and this story made news headlines. Prices of REE went 'sky high' as users tried to secure their supply and governments started inquiries about how they had become so reliant on China. Exploration companies raced to find new and alternative supplies, and manufacturing companies tried to find raw materials to substitute for REE. Two REE mines have opened up since 2010: one, at Mountain Pass , USA, had been the world's main supplier of REE before Chinese dominance and re-opened, but went bankrupt and was forced to close again in 2015; and Mt Weld in Western Australia finally came into production, some 20 years after first exploration and development work. It can often take 10 years from first exploration of any type of ore deposit to opening a mine, so raw materials production is not very flexible in coping with changing demand. By 2014 the World Trade Organisation ruled that China had to remove quotas, which was done in 2015, and by 2017 prices are back to where they were in 2010; and, many exploration projects have come to an end. China still dominates REE supply (Fig. 2) and we will see what happens next.

The story of REE illustrates the problem of what are now called 'critical' raw materials. These are defined as raw materials that are economically important but at potential risk of supply disruption. There has been a variety of studies and measures of criticality. One of the best known was done by the European Commission and first published in 2010, updated in 2014 (European Commission 2014). In Figure 3 the economic importance goes on the x-axis and supply risk on the y-axis. The units are arbitrary and the values are calculated by a methodology to calculate the benefit these raw materials have for the European manufacturing economy and supply risk from concentration of supply from countries with poor governance, less the potential for recycling and substitution. So copper, for example, is economically important, but with many suppliers around the world in lots of different countries (Fig. 4, *opposite*), it is not critical. If one country stopped supplying copper, there are plenty of other options. The amount of recycling is also higher than for other

Figure 3 A schematic graph of criticality based on the European Commission (2014) criticality assessment and showing the current positions of rare earth elements, plus copper for comparison, and four metals associated with South West England: tungsten, indium, lithium and tin. There are no units for the axes and the exact position of the threshold between critical and non-critical raw materials does not have a fixed value; each study decides where to make the divide.



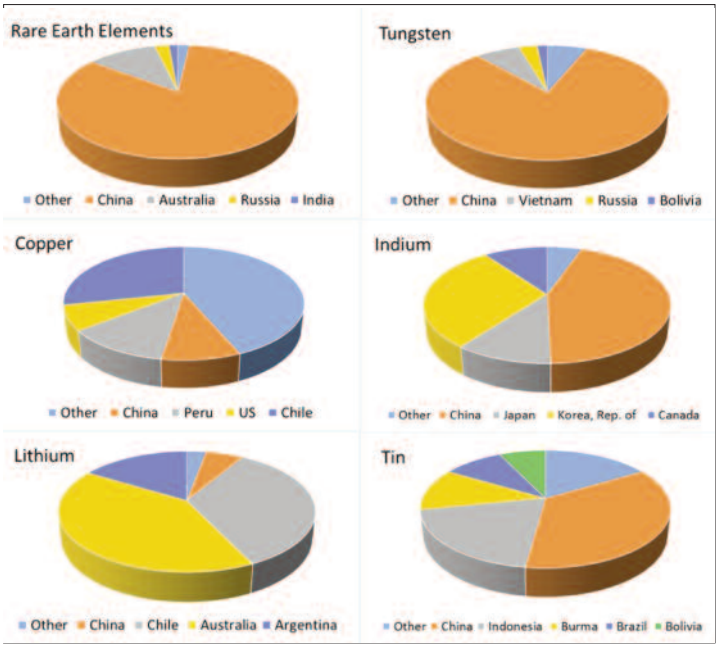


Figure 4 Countries that supply a selection of raw materials, including copper and REE for comparison of a major and critical commodity; three commodities required for high-technology applications, for which there is potential in Devon and Cornwall: tungsten, indium and lithium; and a plot of the volume of copper mined compared to the four minor metals. Mineral statistics are from U.S. Geological Survey (2017).

more specialist metals. At the moment, 20 raw materials are defined as critical raw materials for Europe. Other studies of criticality might relate to different countries or more specific uses, or have different methodologies and thus produce different lists of critical raw materials. The grouping will also change over time. In 2010, the EC listed 14 critical raw materials; in its new study in 2014, it increased this number to 20.

The British Geological Survey has taken a slightly different view to that of the EC, and published a 'risk list' (British Geological Survey 2015; *see* Table 1) that considers seven criteria: production concentration, reserve distribution, recycling rate, substitutability, governance in the countries that are the main producer and main reserve holder, and companion metal fraction (a measure of whether the material is a by-product and thus supply controlled by another commodity). Again, REE top the list because of the dominance of China, and the next four elements are also specialist and minor raw materials for which supply is dominated by China. Gold,is at the bottom of the table because it has many sources and no supply risk is perceived; likewise, for other major commodities such as copper, titanium, zinc and aluminium. In general, it is the specialist raw materials produced in small amounts that are most vulnerable to being critical.

Critical and high technology raw materials in South West England

South West England does not have REE deposits, but hosts potential deposits of some other elements that are on the critical lists. The Drakelands mine at Hemerdon near Plymouth (Wolf Minerals 2017) is the World's fourth largest deposit of the critical metal, tungsten, needed for hard materials in many cutting tools in manufacturing (Brown and Pitfield 2014). Like the REE, supply is dominated by China (Fig. 4), and so although it has received significantly less press coverage, it is still extremely important (Fig. 3). The tungsten occurs as wolframite associated with greisen mineralisation in a large granite dyke, just south of but separate from the Dartmoor granite (British Geological Survey 2011a).

Indium (In) is also classed as a critical raw material for Europe (Fig. 3; European Commission 2014). Nearly half of all production goes into making indium tin oxide for computers, phones and other touch screen applications. Although the production looks more diverse than REE and tungsten (Fig. 4), the problem is that In rarely forms its own minerals and there are no indium mines (Schwarz-Schampera,2014). Instead, In substitutes into other sulphide minerals, especially the zine sulphide, sphalerite. It is only produced as a by-product when the sphalerite, and more rarely copper and tin, ore is refined by smelting, and this increases the supply risk. Significant levels of In have been found around the granites in Cornwall and Devon., located in the sulphide portions of granite-related skarn and vein systems, following highest concentrations of tin but hosted by chalcopyrite and sphalerite (Andersen *et al.* 2016). Although there are no active exploration projects at the moment, this could be of interest in the future.

Lithium (Li) is another specialist metal that may have potential deposits in Cornwall and Devon. It is just outside the critical category at the moment because there are Li mines in several countries, with notable sources from continental brines (salars) in South America and pegmatites such as Greenbushes in Western Australia (Evans *et al.* 2014; Figs 3 and 4). However, if Li continues to be used as the material of choice for lithium ion batteries in electric vehicles, much larger amounts will need to be mined. Potential sources in the South West UK are the reprocessing of Li-bearing micas from china clay processing waste (e.g. Siame and Pascoe 2011; British Geological Survey 2016), and extracting Li from underground brines in granite and related areas (Beer *et al.* 1978; *TheGuardian* 2017).

Tin is perhaps the most famous metal associated with South West England, and this has been calculated as important, but just outside the critical category for Europe (Fig. 3), with a reasonable diversity of sources, including China and Indonesia as the major providers (Fig. 4); and higher levels of recycling than the very specialist metals.

Table 1 A sample of the British Geological Survey Risk List 2015, showing the top five highest-risk elements (1–5, red) and bottom five lowest risk elements (36–40, green)

No.	*name*		*risk*	*Country*	*No.*	*name*		*risk*	*country*
1	Rare earths	REE	9.5	China	36	Titanium	Ti	4.8	Canada
2	Antimony	Sb	9.0	China	37	Copper	Cu	4.8	Chile
3	Bismuth	Bi	8.8	China	38	Zinc	Zn	4.8	China
4	Germanium	Ge	8.6	China	39	Aluminium	Al	4.8	Australia
5	Vanadium	V	8.6	China	40	Gold	Au	4.5	China

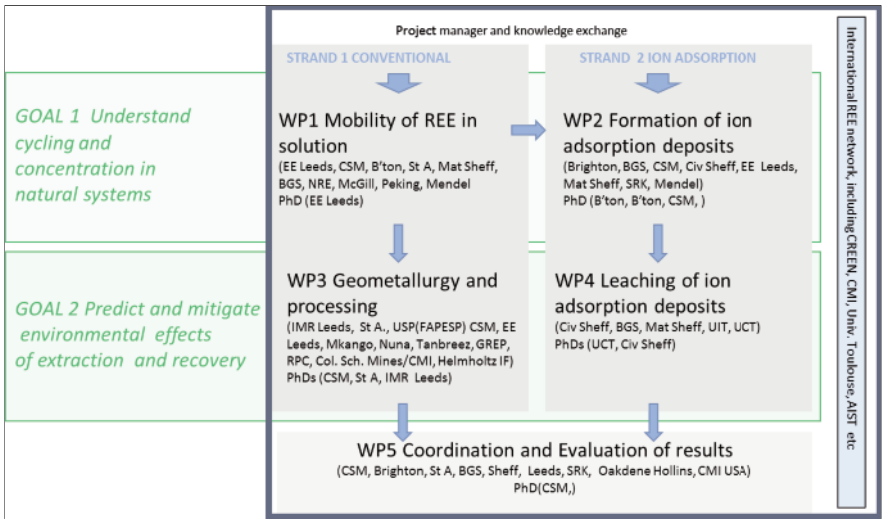
UK research on security of supply of critical raw materials

There are various strategies to overcome the problem of criticality. One solution is to try to substitute another material for the critical raw material. The problem is that by definition, critical raw materials are difficult to substitute. Manufacturers who can use alternatives will do so as soon as the price rises, and if others are encouraged to substitute, this can actually increase the problem of criticality for the remaining users. A second idea, is the obvious point that once a material has been mined, it should be kept in circulation by re-use and then by recycling. Not only is this resource efficient, it is also a good way to diversify supply. Unfortunately, it is also very difficult for many materials. In many applications, the components using the critical raw materials are complex and too expensive to recycle to recover the small amounts involved, and are thus low-value critical raw materials. A third solution is the geological one of providing additional, diverse and secure new deposits for primary raw materials supply. In the UK, the Natural Environment Research Council, and the Engineering and Physical Sciences and Research Council have sponsored a research programme called 'Security of Supply of Minerals' (www.bgs.ac.uk/sosminerals/). There are four large projects in the programme and each consortium has *c*. £2.5 million of research council support, plus additional resources from industry partners and international collaborators. Each consortium in the programme is tackling two goals. The first is to understand how the critical raw materials are concentrated in order to improve exploration targeting, and the second is to make mining and processing more efficient and environmentally friendly.

One of the research projects is called 'SoS RARE' and concentrates on the REE. The others centre on cobalt (CoG3), tellurium and selenium (TEaSE) and deep-sea minerals (MarineE-tech). Research is done in large collaborative teams, divided into work packages to make manageable units (Fig. 5). Most large projects also have international participants, for example, colleagues from Germany, Canada, South Africa, Japan, Czech Republic and even China are involved in SoS RARE, as these countries are also industry partners who support the research and will benefit directly from it.

The SoS RARE project is helping the search for new supplies of REE by working on how fluids concentrate heavy and light REE so that it is possible to predict better when to search for neodymium and the heavy REE, which are the most in demand at the moment. Geological and mineralogical work is combined closely with work on minerals processing to concentrate the REE minerals and to dissolve and separate REE. This is a crucial energy-intensive stage where there is great potential for making the extraction process more environmentally friendly. As part of the quest for environmentally-friendly ores, the project is examining, in its Strand 2, the formation and processing of a group of REE deposits called 'ion adsorption' deposits (*see below)*, to try to understand where else besides China these deposits form and to establish if there is potential for more environmentally-friendly ways to extract the REE.

Figure 5 Structure of the SoS RARE project on 'Multidisciplinary research towards a secure and environmentally sustainable supply of critical rare earth elements (Nd and HREE)'. The project consortium has 17 academic investigators at 6 UK research organisations, plus 7 post-doctoral scientists, 6 PhD students, 8 overseas collaborators and 10 industry partners ***(www.sosrare.org)****.*


Project manager and knowledge exchange
STRAND 1 CONVENTIONAL
STRAND 2 ION ADSORPTION
GOAL 1 Understand cycling and concentration in natural systems
GOAL 2 Predict and mitigate environmental effects of extraction and recovery
WP1 Mobility of REE in solution
(EE Leeds, CSM, B'ton, St A, Mat Sheff, BGS, NRE, McGill, Peking, Mendel
PhD (EE Leeds)
WP2 Formation of ion adsorption deposits
(Brighton, BGS, CSM, Civ Sheff, EE Leeds, Mat Sheff, SRK, Mendel)
PhD (B'ton, B'ton, CSM,)
WP3 Geometallurgy and processing
(IMR Leeds, St A., USP(FAPESP) CSM, EE Leeds, Mkango, Nuna, Tanbreez, GREP, RPC, Col. Sch. Mines/CMI, Helmholtz IF)
PhDs (CSM, St A, IMR Leeds)
WP4 Leaching of ion adsorption deposits
(Civ Sheff, BGS, Mat Sheff, UIT, UCT)
PhDs (UCT, Civ Sheff)
WP5 Coordination and Evaluation of results
(CSM, Brighton, St A, BGS, Sheff, Leeds, SRK, Oakdene Hollins, CMI USA)
PhD(CSM,)
International REE network, including CREEN, CMI, Univ. Toulouse, AIST etc

REE geochemistry

The geochemistry of the REE is controlled by the smooth variation in size of the REE^{3+} cations found in nature, which is largest for the low atomic number REE, lanthanum (La), and then becomes progressively smaller as the atomic number increased to lutetium (Lu). This is counter intuitive and called the 'lanthanide contraction' (Fig. 6, *opposite*). Yttrium is the same cation charge and size as holmium. This close relationship in size and charge means that the REE are always found together in nature; but given the change in size from La to Lu, there is a gentle fractionation between the light (lowest atomic number) and heavy (highest atomic number) REE. Nature makes its division between light and heavy REE at gadolinium (Gd), where the structure of REE phosphate minerals changes from monazite $(LREE)PO_4$ to xenotime $(HREE)PO_4$. There are two exceptions to this rule of gentle fractionation: in oxidising environments, cerium forms Ce^{4+} and in reducing environments, Europium can be most stable as Eu^{2+}. The change in oxidation state and cation size means that these two cations can be fractionated from the rest of the REE series. For economic geologists, the challenge is that apart from Ce and Eu, the REE never occur alone in nature. Neodymium is particularly sought after at the moment for use in neodymium iron boron permanent magnets, but there are no deposits of just Nd. A Nd deposit is always likely to contain much higher quantities of La and Ce than of Nd.

The diversity of REE deposits

REE in nature are a bit like REE in manufactured goods in that they are all around us but almost always in low quantities. This wide distribution at trace-element levels makes REE useful for many geological studies, for example, in modelling of fractionation of melts in igneous petrology.

Finding REE in quantities that are economic to mine is more difficult. However, REE are not particularly rare. Cerium, one of the light REE, is as abundant in the crust as copper, and even though the heavy REE have much lower abundances, they are still more abundant than silver (U.S. Geological Survey 2002). There is more good news in that there are many different geological environments that can potentially concentrate REE

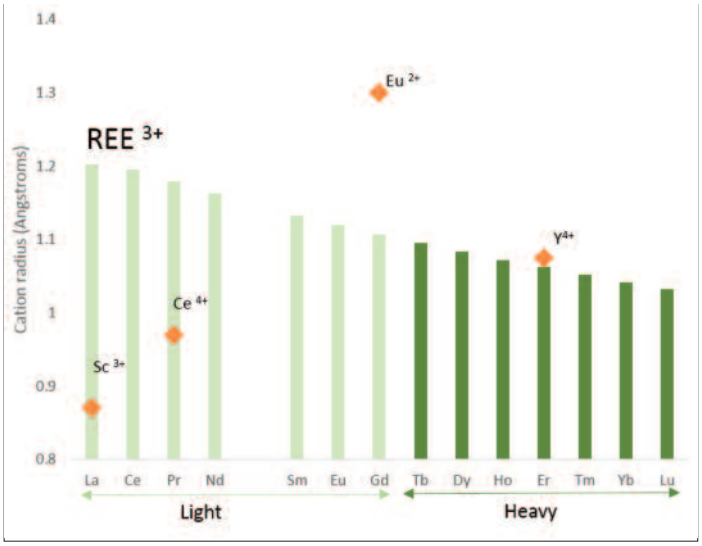


Figure 6 The lanthanide contraction, which controls the geochemical behaviour of REE. In nature the divide between light and heavy REE is between gadolinium (Gd) and terbium (Tb) where the REE phosphate mineral structure changes from monazite to xenotime. Chemists tend to put the divide between samarium (Sm) and Europium (Eu). Values for ionic radii are from Shannon (1976).

to create economic deposits (Fig. 7, *overleaf*). Reviews of REE ore deposits are given in British Geological Survey (2011a), Chakhmouradian and Wall (2012), Wall (2014), Goodenough *et al.* (2016), and Verplanck and Hitzman (2016).

The majority of deposits that are mined or under exploration are associated with carbonatites and alkaline rocks. These igneous rocks have some of the most unusual and diverse compositions of any rocks on Earth. Carbonatites are made of at least 50% carbonate, but nevertheless formed by crystallisation from molten magma and alkaline rocks, and silicate igneous rocks with higher sodium and potassium to silica ratios than most other igneous rock types. Both start off as small degree partial melts from the mantle, which is a first step in enriching them in REE. Further magma fractionation, and often hydrothermal processes — even lateritic weathering that removes soluble minerals and concentrates REE in residual minerals — serve to concentrate REE up to weight percent levels, at which point they may be economic to mine.

The oldest mined type of REE deposits are mineral sands, literally beach sands, in which the REE minerals, monazite-(Ce) and (in lesser quantities) xenotime-(Y) are concentrated along with other tough and heavy minerals such as rutile, ilmenite, magnetite and zircon in bands among quartz-rich beach sands. The deposits mined in India are formed by this process. Similar types of deposits that occur along rivers (alluvial) and have been preserved in the geological record (palaeoplacers) may also be of interest.

The deposits in China that provide the world's heavy REE are rather unusual in that they are weathered granitic rocks, in which the REE have been released from the original igneous and hydrothermal minerals and are now adsorbed onto the surface of clays, such as kaolinite, that formed during the weathering process. Adsorbed cations are not part of the mineral structure but are simply attracted to the surface of the mineral. This means that they can easily be leached out of the clays by ion exchange reagents. This can even be done by *in situ* mining. Given the higher prices paid for heavy REE, these kinds of deposits can contain REE grades as low as 500ppm.

There are also many other types of rocks that are being considered as potential REE resources, including several where there is no obvious connection to alkaline rocks or to carbonatites, but where hydrothermal fluids appear to have concentrated REE and deposits where REE concentrations are low but might be produced as by-products alongside the main commodity. These include phosphate deposits, mined as raw materials for fertiliser, and bauxite, the ore of aluminium.

REE in carbonatites

The majority of working mines are connected in some way with the igneous rocks called carbonatites (Fig. 8). Carbonatites are intracontinental rocks, usually intruded into Precambrian crust and often formed associated with rift valleys (Woolley and Bailey 2012). Volcanic carbonatites, such as the natrocarbonatite lavas and ashes erupted form the only active carbonatite volcano at Oldoinyo Lengai, Tanzania rarely contain high concentrations of REE. The highest levels of REE are found in subvolcanic carbonatites, where the magma seems to have been most fractionated to cause the highest degree of enrichment. The concentration of REE can reach over 10 wt% in places as in some of the bastnäsite-bearing carbonatite at Mountain Pass, California (Castor 2008). In a number of cases, the REE are interpreted as having become concentrated in a fractionating

Figure 8 Carbonatite dyke at Lofdal, Namibia. Another carbonatite environment where heavy REE have been concentrated, forming xenotime-(Y), which is being studied as part of the SoS RARE project (Sam Broom-Fendley for scale).

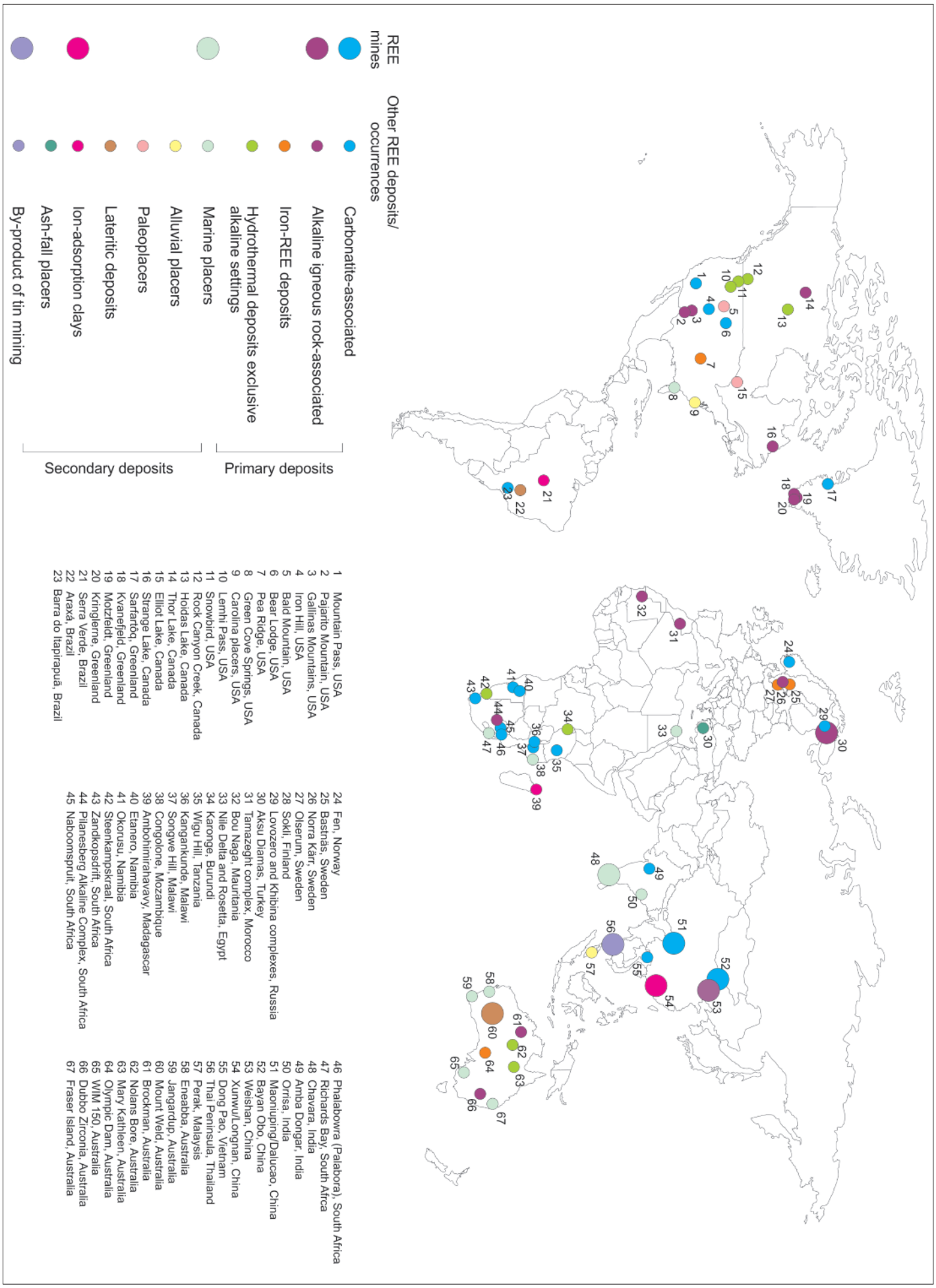


Figure 7 Mines and deposits of rare earths. Contains British Geological Survey materials (© NERC [2011], see British Geological Survey 2011b). The lateritic deposits listed here are in weathered carbonatite.

magma, but then precipitated right at the final stages of crystallisation, in transition environments between magma and hydrothermal fluid, where unidirectional textures suggest a pegmatite-like environment of formation (Fig. 9). Although at first glance the crystals look big, they have usually been altered by hydrothermal fluids derived from the magma and are now pseudomorphed by a fine-grained, mixed assemblage of minerals such as monazite-(Ce), strontianite and baryte.

In the SoS RARE project, we are particularly interested in learning about environments in which the heavy REE can be concentrated. Such environments are rare in carbonatites because the processes of partial melting and igneous fractionation all tend to preferentially concentrate the light REE. However, it has been found that where hydrothermal alteration has been pervasive, such that it has changed the nature of original minerals, such as apatite, as in the Songwe Hill carbonatite, Malawi, with the right fluids, temperatures and mineral components it is possible to produce higher concentrations of the sought after heavy REE (Broom-Fendley *et al.* 2017).

Figure 9 Unidirectional crystallisation textures (nucleation centre top-left and centre towards lower-left) shown by pseudomorphs of green monazite-(Ce), strontianite, baryte (both white) in ferroan dolomite carbonatite, Kangankunde, Malawi (width of picture c. *60mm).*

The challenge of processing REE deposits

Finding rocks with high enough concentrations to make them economical to mine is just the start of the story. A particular challenge is finding efficient and environmentally-friendly ways to extract the REE minerals from the ore and the individual REE from the minerals. The crystallisation textures of REE minerals can be complex, with small crystals and fine intergrowths (Fig. 10; Wall 2014). Little research on minerals processing of REE deposits was done until the surge in exploration interest from 2010, and many minerals that now form potential ore deposits have never been commercially mined and processed (Table 2; Jordens *et al.* 2013; Krishnamurthy and Gupta 2016; Cui and Anderson 2016). Even where processing routes are well established, it is necessary to do detailed mineralogical and geometallurgical work (connecting geology to minerals processing behaviour) before it is possible to design an efficient processing method. Processes for bastnäsite and monazite have been well

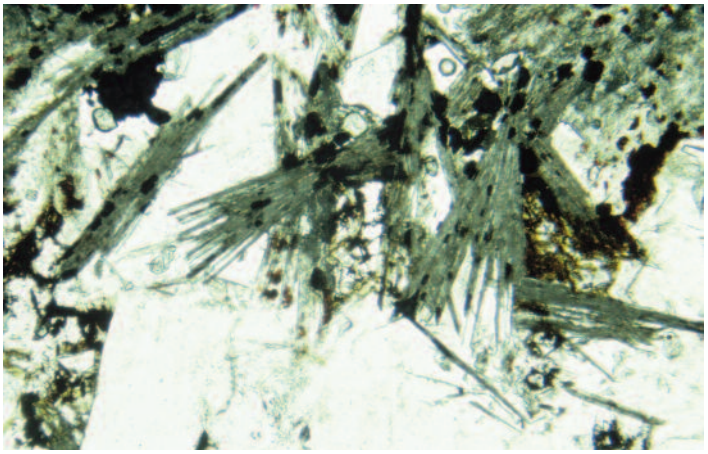


Figure 10 Photomicrograph of sheaves of bastnäsite-(Ce) needles in quartz-bearing carbonatite, Kangankunde, Malawi (Wall 2000), in plane polarised light (width of image c. *0.6mm).*

Table 2 Minerals in REE ore deposits and established processing techniques

mineral	*formula*	*processing techniques used*
processing techniques well-established		
bastnäsite-(Ce)	$CeCO_3F$	flotation
monazite-(Ce)	$CePO_4$	flotation or gravity/electrostatic/magnetitc
xenotime-(Y)	YPO_4	gravity/electrostatic/magnetic (flotation)
loparite-(Ce)	$(Na,Ce,Sr)(Ce,Th)(Ti,Nb)_2O_6$	gravity / magnetic[1]
apatite	$Ca_5(PO_4)_3F$	flotation
minerals similar to bastnäsite so processing likely to be similar		
parisite-(Ce)	$CaCe_2(CO_3)_3F_2$	flotation
synchysite-(Ce)	$CaCe(CO_3)_2F$	flotation
minerals not yet concentrated in commercial operations		
ancylite-(Ce)	$SrCe(CO_3)_2(OH)\ H_2O$	scrubbing, acid dissolutio
eudialyte	$Na_{15}Ca_6Fe_3Zr_3Si(Si_{25}O_{73})(O,OH,H_2O)_3(Cl,OH)_2$	flotation[2]
steenstrupine-Ce)	$Na_{14}Ce_6Mn_2Fe_2Zr(PO_4)_7Si_{12}O_{36}(OH)_2\ 3H_2O$	flotation[3]

Formulae are taken from www.ima-mineralogy.org. Ce represents the light REE, which are Ce-dominant; Y represents the HREE, which are Y-dominant. Based on Wall (2014), with additional information from [1]Hedrick et al. *(1997), Jordens* et al. *(2013) [2]Stark* et al. *(2016), and [3]Greenland Minerals and Energy (2015).*

established, but will still vary depending on the deposit characteristics (Krishnamurthy and Gupta 2016). For example, in mineral sands, the monazite grains are usually free from other minerals and can be separated by cheap and chemical-free physical separation methods such as gravity separation, whereas in lateritic deposits, monazite is likely to be intergrown with minerals such as iron oxides and must be ground to a finer grain size and separated by flotation, requiring additional energy and chemicals. Minerals such as ancylite, parisite, synchysite in carbonatites and eudialyte, steenstrupine and allanite in alkaline rocks were poorly understood until a flurry of recent research, which is still yet to be put into practice at an industrial scale. However, many more investigations are needed before any of these minerals are as well understood as bastnäsite and monazite.

Once the mineral is concentrated, it is then necessary to dissolve it up to release the REE, and this is a chemical-intensive process. Then comes an even more chemical-intensive process to separate the individual REE from each other and produce the single REE intermediate products that manufacturers need (Krishnamurthy and Gupta 2016).

SoS RARE is working on improvements to conventional techniques for separating REE minerals, such as flotation, and also working on potential new methods for ion-adsorption deposits, and using a type of ionic liquids for separating REE from each other.

Conclusions

A wider range of raw materials is needed now than ever before as we exploit the specialist properties of the chemical elements in our high-technology communication, clean energy generation, transportation and computing systems. Some of these elements are only needed in small quantities, which means that in many cases the amounts mined per year are more than one hundred times lower than a major metal such as copper. These specialist raw materials can therefore be very important economically, but vulnerable to supply disruption and are given the term 'critical raw materials'.

Mining is a global industry and the research and innovation skills developed in South West England can be applied for worldwide problems such as the search for secure and environmentally-friendly sources of REE. The Natural Environment Research Council is funding a programme called SoS Minerals to help secure several critical raw materials needed for environmental technologies.

There are some critical raw materials in the South West UK. Most notably, the world's fourth largest deposit of tungsten is being mined at Drakelands Mine, near Hemerdon, Devon. There is also some potential for indium. Lithium is of interest, even though not defined as 'critical' at the moment, it is likely to be in high demand for batteries in electric vehicles; and tin should not be forgotten, as it is also a key ingredient of many electronic devices.

Acknowledgements

We are grateful to the Open University Geological Society for the invitation to participate in their 2016 Annual Symposium in Exeter, to Isabel O'Brien for transcribing the first part of the original lecture and to David Jones for editing the article. The SoS RARE project is funded by NERC grant NE/M011429/1. Camilla Owens' PhD study is also co-funded by Mkango Resources Ltd.

References

Andersen, J. C. Ø., Stickland, R. J., Rollinson, G. K., and Shail, R. K.,2016 'Indium mineralisation in SW England: host parageneses and mineralogical relations'. *Ore Geol Rev* **78**, 213–38 **http://dx.doi.org/10.1016/j.oregeorev.2016.02.019**

Beer, K. E., Edmonds, W. M., and Hawkes, J. R. 1978 'A preliminary look at lithium in the United Kingdom', *in* Penner, S. S. (ed) 'Lithium needs and resources (Corning, N.J., 1977)'. *Energy* **3**, 281–92. Oxford: Pergamon Press

British Geological Survey 2011a 'Tungsten mineral profile, British Geological Survey, Nottingham, U.K'. **http://www.bgs.ac.uk/mineralsUK/statistics/mineralProfiles.html** (accessed 5.2.2017)

British Geological Survey 2011b 'Rare earths mineral profile, British Geological Survey, Nottingham, U.K'. **http://www.bgs.ac.uk/mineralsUK/statistics/mineralProfiles.html** (accessed 1.3.2017)

British Geological Survey 2015 'Risk list 2015'. **http://www.bgs.ac.uk/mineralsuk/statistics/riskList.html** (accessed 4.2.2017)

British Geological Survey 2016 'Lithium mineral profile, British Geological Survey, Nottingham, U.K' **http://www.bgs.ac.uk/mineralsUK/statistics/mineralProfiles.html** (accessed 5.2.2017)

Broom-Fendley, S., Brady, A. E., Wall, F., Gunn, G., and Dawes, W. 2017 'REE minerals at the Songwe Hill carbonatite, Malawi: HREE-enrichment in late-stage apatite'. *Ore Geol Rev* **81**, 23–41 **http://dx.doi.org/10.1016/j.oregeorev.2016.10.019**

Brown, T., and Pitfield, P. 2014 'Tungsten', *in* Gunn, G. (ed) *Critical Metals Handbook*. Chichester: John Wiley & Sons, 385–413

Castor, S. B. 2008 'The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California'. *Canadian Mineralogist* **46**, 779–806. **DOI : 10.3749/canmin.46.4.779**

Chakhmouradian, A. R., and Wall, F. 2012 'Rare earth elements: minerals, mines, magnets (and more)'. *Elements* **8**, 333–40. **DOI:10.2113/gselements.8.5.333**

Cui, H., and Anderson, C. G. 2016 'Fundamental studies on the surface chemistry of ancylite, calcite, and strontianite'. *J Sustainable Metal* **3**, 1–14. **DOI: 10.1007/s40831-016-0097-x**

European Commission,2014 'Report on critical raw materials for the EU'. Report of the Ad Hoc Working Group on defining critical raw materials, May 2014

Evans, T., Piper, D. M., Kim, S. C., Han, S. S., Bhat, V., Oh, K. H., and Lee, S. H. 2014 'Ionic liquid enabled FeS2 for high-energy-density lithium-ion batteries'. *Advanced Materials* **26**, 7386–92

Goodenough, K. M., Schilling, J., Jonsson, E., Kalvig, P., Charles, N., Tuduri, J., Deady, E. A., Sadeghi, M., Schiellerup, H., Müller, A., Bertrand, G., Arvanitidis, N., Eliopoulos, D. G., Shaw, R. A., Thrane, K., and Keulen, N. 2016 'Europe's rare earth element resource potential: an overview of REE metallogenetic provinces and their geodynamic setting'. *Ore Geol Rev* **72**, 838–56

Graedel, T. E., Harper, E. M., Nassar, N. T., and Reck, B. K. 2015 'On the materials basis of modern society'. *PNAS* **112**, 6295–6300. **DOI: 10.1073/pnas.1312752110**

Greenland Minerals and Energy Ltd 2015 **http://www.ggg.gl/docs/ASX-announcements/Refinery-Update-ContinuousLeachTestwork.pdf** (accessed 9.2.2017)

Hatch, G. P. 2012 'Dynamics in the global market for rare earths'. *Elements* **8**, 341–6. **DOI: 10.2113/gselements.8.5.341**

Hedrick, J. B., Sinha, S. P., and Kosynkin, V. D. 1997 'Loparite, a rare-earth ore (Ce, Na, Sr, Ca)(Ti, Nb, Ta, Fe^{+3})O_3'. *J Alloys and Compounds* **250**, 467–70

Jordens, A., Cheng, Y. P., and Waters, K. E. 2013 'A review of the beneficiation of rare earth element bearing minerals'. *Minerals Engineering* **41**, 97–114

Kishnamurthy, N., and Gupta, C. K. 2016 *Extractive Metallurgy of Rare Earths* (2nd edn). Boca Raton, USA: CRC Press

Schwarz-Schampera, U. 2014 'Indium', *in* Gunn, G. (ed) *Critical Metals Handbook*. Chichester: John Wiley & Sons, 204–29

Shannon, R. D. 1976 'Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides'. *Acta Crystallographica Section A* **32**, 751–67
DOI: 10.1107/S0567739476001551 (accessed via **http://www.knowledgedoor.com/2/elements_handbook/shannon-prewitt_effective_ionic_radius.html#sthash.uv4DSn27.dpuf** (accessed 9.2.2017)

Siame, E., and Pascoe, R. D. 2011 'Extraction of lithium from micaceous waste from china clay production'. *Minerals Engineering* **24**, 1595–1602

Stark, T., Silin, I., and Wotruba, H. 2016 'Mineral processing of eudialyte ore from Norra Kärr'. *J Sustainable Metal* **3**, 1–7.
DOI: 10.1007/s40831-016-0073-5

TheGuardian 2017 'Mining firm hopes to extract lithium from Cornwall's hot springs'. Thursday 19 January 2017 11.00 GMT. **https://www.theguardian.com/uk-news/2017/jan/19/cornwall-mining-firm-extract-lithium** (accessed 5.2.2017)

U.S. Geological Survey 2002 'Rare Earth Elements—Critical Resources for High Technology, Fact Sheet 087-02' (modified 2005). **https://pubs.usgs.gov/fs/2002/fs087-02** (accessed 5.2.2017)

U.S. Geological Survey 2017 'Mineral commodity summaries 2017: U.S. Geological Survey'. **http://dx.doi.org/10.3133/70180197** (accessed 4.2.2017)

Verplanck, P. L., and Hitzman, M. 2016 *Rare Earth and Critical Elements in Ore Deposits*. Littleton, Colorado: Soc Econ Geologists

Wall, F. 2000 'Mineral chemistry and petrogenesis of rare earth-rich carbonaites with particular reference to the Kangankunde carbonatite, Malawi'. Unpubl PhD thesis, University of London

Wall, F. 2014 'Rare earth elements', *in* Gunn, G. (ed) *Critical Metals Handbook*. Chichester: John Wiley & Sons, 312–39

Wolf Minerals 2017 'Drakelands Mine'.
http://www.wolfminerals.com.au/irm/content/drakelands-mine.aspx?RID=324 (accessed 5.2.2-17)

Woolley, A. R., and Bailey, D. K. 2012 'The crucial role of lithospheric structure in the generation and release of carbonatites: geological evidence'. *Mineralogical Mag* **76**, 259–70.
https://doi.org/10.1180/minmag.2012.076.2.02

Book review

Li, Z. X., Evans, D. A. D., and Murphy, J. P (eds) 2016 *Supercontinent Cycles through Earth History*. Bath: Geol Soc Spec Publ 424 (ISBN 978-1-86239-733-0; hardback, 297pp; £110)

This Special Publication outlines and illustrates the supercontinent-cycle hypothesis, and is part of a continuing research programme on supercontinental cycles and global geodynamics. This attributes planetary-scale episodic tectonic events to an intrinsic self-organising mode of convection.

Such tectonic events are fundamentally due to the buoyancy of continental crust, which resists subduction during the closure of old ocean basins, leading to the consequent reorganisation of mantle convection cells and thus the opening of new ocean basins. This process occurs on a cycle of approximately 500 to 700 million years.

This work started with the ancestral continent of Pangea, considered by Alfred Wegner. Then, as geological knowledge increased and with the plate tectonics revolution, geologists could study Palaeozoic and Precambrian oceans and continents; and subsequently move on to determine cycles and supercontinents.

The working definition of a supercontinent is that it contains at least 75% of the extant continental area from any given age. Thus this definition includes Pangea at 85–90%, but excludes Gondwana at *c.* 60% and our current Eurasia at only 35%. The known supercontinents are therefore Pangea (200–300Ma), Rodina (750–900Ma), Nuna (1350–1550Ma) and the hypothetical Kenorland Neoarchean-Paleoproterozoic supercratons (2100–2500Ma). Further articles then proceed to investigate the transition cycles between these supercontinents.

The interaction of the supercontinent cycles and the deep mantle is used to investigate how the Earth's tectonic engine works. This may be driven by the lower mantle thermal anomalies (superplumes). The supercontinental transitions (cycles) can be described as extroversion, introversion and orthoversion. Extroversion is when the next supercontinent forms over the ocean surrounding the previous one; introversion is the closing of Atlantic-type oceans in the Wilson cycle to form a new supercontinent in the same location as the previous one; and orthoversion is when new pairs of large, low shearwave velocity provinces (LLSVPs) are created on the old supercontinent, but located in the mantle at precisely 90 degrees away from the previous LLSVPs.

Looking at the main cycles, we know too little about Kenorland-Nuna to characterise that cycle. Nuna-Rodina is mainly introversion, with some extroversion. Rodina-Gondwana is mainly extroversion. And Gondwana to Pangea is introversion. The next (future) continent of Amasia could be characterised by introversion (Atlantic reclosing), extroversion (Pacific closing) or orthoversion (Artic Ocean closing).

After the introductory paper, 'Four-dimensional context of Earth's supercontinents', further articles provide snapshots in time to investigate specific examples and areas further further in the following papers: 'Palaeomagnetism, geochronology and geochemistry of the Palaeoproterozoic Rabbit Creek and Powder River dyke swarms'; 'Implications for Wyoming in supercraton Superia'; 'Australia and Nuna'; 'Metallogeny and its link to orogenic style during the Nuna supercontinent cycle'; 'Palaeomagnetism and U–Pb geochronology of *c.* 1570 Ma intrusives from Åland archipelago, SW Finland – implications for Nuna'; 'Using palaeomagnetism to determine late Mesoproterozoic palaeogeographic history and tectonic relations of the Sinclair terrane'; 'Namaqua orogen, Namibia'; 'Palaeomagnetic and geochronological data from Late Mesoproterozoic redbed sedimentary rocks on the western margin of Kalahari craton, Return to Rodinia? Moderate to high palaeolatitude of the São Francisco/Congo craton at 920Ma, Palaeomagnetism and geochronology of mid-Neoproterozoic Yanbian dykes, South China: implications for a *c.* 820–800Ma true polar wander event and the reconstruction of Rodinia'; 'Tectonostratigraphic evolution of the *c.* 780–730Ma Beck Spring Dolomite'; 'Basin formation in the core of Rodinia'; 'An eastern Mediterranean analogue for the Late Palaeozoic evolution of the Pangaean suture zone in SW Iberia'; 'How subduction broke up Pangaea with implications for the supercontinent cycle'.

The first paper ends with 10 outstanding questions for the advancement of supercontinent research — starting with how may supercontinents have existed on Earth — and ending with 'was there a Kenorland or were there separately drifting supercratons at 2.5Ga'? Certainly a large and ambitious field of research.

— John Lonergan, BSc Hons (Open), FGS

Industrial Minerals in south-west England

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Introduction

Historically, south-west England has been a major source of ores of metals, including tin, copper, iron, zinc and lead. Although a few mines were operating until the 1980s, the last underground one (South Crofty in Cornwall), which extracted tin ore, eventually closed in 1998. In 2015, a new open-pit tungsten mine at Hemerdon in Devon (Drakelands Mine) began operation (see www.wolfminerals.com.au). It has a projected life of 10–15 years. Recently there has been further active exploration for new metal ore resources in Devon and Cornwall; but, at present Drakelands is the only operating metal ore mine in the United Kingdom. There are, however, more than 2,000 other locations where minerals and rocks are extracted in the UK from open pits, quarries and underground mines. Apart from a few open-pit coal mines, these are entirely devoted to the extraction of industrial minerals.

Industrial minerals are a wide ranging group of Earth resources mined in almost every country of the world. They include many common rocks and minerals, numerous rare ones, and incorporate aggregates and other rocks and minerals used in construction. This article briefly reviews the significance and use of industrial minerals in the UK, with further emphasis on industrial minerals from south-west England, particularly limestone, china clay and ball clay. A review of the geological setting for industrial mineral resources in the UK and in their wider context can be found in Scott (2008; 2011).

Table 1 Approximate values of industrial minerals produced in the United Kingdom in 2014 from British Geological Survey data (Idoine 2016)

rock or mineral	*value (£000)*	*amount (thousand tonnes)*
Sand and gravel	643	61,127*
Limestone and dolomite	663	70,030
Chalk	57	3,312
Igneous rock	333	43,700
Sandstone	122	12,500
Silica sand	55	3,948
Clay and shale	59	6,806
China clay (kaolin)	129	1,090
Ball clay	48	733
Salt	255	4,690
Potash	226	1,000
Fluorspar	4	24
Gypsum and anhydrite	17	1,200
Barytes	n/a	44
Miscellaneous minerals	70	—

n/a Data not available.
* Includes both land and marine sand and gravel.
Miscellaneous minerals are slate, barytes, chert and flint, fireclay, peat, and talc.

Industrial minerals in the United Kingdom

In 2014, the latest date for which information is available, the value of minerals produced in the UK as estimated by the British Geological Survey is just over £28.15 billion (Idoine *et al*. 2016), of which £24.84 billion is natural gas and crude petroleum, £660 million is coal, £0 is metal ores and £2.65 billion is industrial minerals. Table 1 shows a breakdown of the data in terms of the individual minerals and rocks. The data are claimed to be calculated on an ex-works sales basis. If some added value for extraction is included, data from the CBI Mineral Group (CBI 2016) show that the total for industrial minerals is £4.4 billion (CBI 2016, 2013 data). Further data (CBI 2016) show that the turnover of the UK non-energy minerals sector (i.e. industrial minerals) is £14.54 billion; it employs 34,000 people and has the highest productivity of all industries (£133k per employee), except for oil and gas extraction (£218k) and real estate (£525k). Average productivity in the UK is £51k per employee. Industrial minerals extraction, therefore, is an important and efficient activity within the UK economy.

The major minerals and rocks extracted in the UK are limestone and dolomite, sand and gravel, igneous rocks and sandstone (Table 1). They are relatively low-value-per-tonne commodities. The major uses of each of these are in construction, particularly as aggregates in concrete, the building and repair of roads, and other infrastructure developments and maintenance. Chalk is used in construction as a low-grade aggregate. Silica sand is used in mortars and plastering, as well as for sports surfaces and sewage filtration. It is the principal raw material for the manufacture of glass. Clay and shale are the raw material for brickmaking. Several industrial minerals are used in the manufacture of ceramics (china clay, ball clay, other clays, silica sand and limestone). Some are sources for chemicals (limestone, salt and fluorspar) or fertilizers (limestone and potash). Limestone and clay or shale are pulverised together and calcined in a rotary kiln to make cement. Gypsum is added to the raw cement to retard the setting. Gypsum is also the main raw material for plaster and plasterboard. Essentially, the industrial minerals produced in the UK provide the raw material feedstocks for the basic (i.e. essential) industries of the nation (see Scott 2008, 2011). Table 2 *(overleaf)* shows these industries along with the industrial minerals extracted in the UK that are used in them.

As a more detailed example, a summary of the uses of limestone is given in Table 3 *(overleaf)*. The uses are divided according to the size of the product (Scott and Dunham 1984). Although some mines and quarries extract limestone for a single use, such as building stone, others make a wide range of products for several different markets. For example, a large limestone quarry in the Peak District of Derbyshire might make limestone aggregates, as well as products for the glass industry, and powdered fillers and extenders. It might also have kilns to make lime. The limestone would need to be of high or very high purity (i.e. more than 97% or 98.5% $CaCO_3$ respectively) to be suitable for several of these uses. Several limestone quarries that make aggregates as a primary product also use the fines generated in the crushing

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Table 2 Industrial minerals produced in the UK and their uses as feedstocks in basic industries

Construction feedstock:
limestone, dolomite, igneous rock, sandstone, sand and gravel*, gypsum, dimension stone (slate, granite, limestone)
Ceramic feedstock:
limestone, dolomite, silica sand, kaolin (china clay)*, ball clay*, fireclay, brick clay
Chemical feedstock:
limestone, dolomite, gypsum, potash, salt, fluorite, barytes
Agriculture / horticulture feedstock:
limestone, dolomite, peat, potash*, salt, gypsum
Iron and steel feedstock:
limestone, dolomite, silica sand, fluorite
Consumer products feedstock (e.g. plastics, paint, paper):
limestone, dolomite, kaolin*, talc

* significant exports

process as agricultural lime. Dolomite is also used as an aggregate, although high purity dolomite is also an important raw material for making refractories and fluxes used in the iron and steel industry.

Shap Beck is a typical large limestone quarry (Fig. 1). The quarry is in the Carboniferous limestone, Knipe Scar Limestone Formation. Crushed rock aggregate, coated roadstone, ready-mixed concrete and agricultural lime are produced, along with the feedstock for the Shapfell Lime Works, which has three modern lime kilns and provides lime flux for the steel industry and lime products for other applications. The limestone is of very high purity with a typical composition of 55.93% CaO, 0.22% MgO, 0.43% SiO_2, 0.08% Fe_2O_3 and 0.05% Al_2O_3 (Young *et al.* 2001). Other large quarries in limestone of Carboniferous age are located in North Yorkshire, Derbyshire, North and South Wales, and the Mendips. Other geological ages that host limestone quarries in the UK include the Proterozoic, Cambrian, Silurian, Devonian, Permian (limestone and dolomite), Jurassic and Cretaceous (including the Chalk) (Cameron *et al.* 2014).

Table 3 Summary of the uses of limestone, divided according to the size of the product

size	*use*
>1m	cut / ornamental stone
	armour stone
>30cm	building stone
1-40cm	aggregates for concrete, road base, etc.
5-20cm	feed stone for lime kiln
0.2-5cm	chemicals
	glass
3-8cm	filter bed stone
3-8mm	poultry grit
<4mm	agriculture
<3mm	iron ore sinter
<0.2mm	filler and extender in paint, plastics, rubber etc.
<0.2mm	asphalt filler
<0.2mm	mild abrasive
<0.2mm	glazes and enamels
<0.1mm	flue gas desulphurisation
Various sizes	bulk fill
Pulverised and mixed with clay or shale and clacined.	cement

Figure 1 Shap Beck Quarry, Cumbria, showing quarry faces and processing plant (dated 2014). Products from the quarry include aggregates and stone for the nearby lime kilns.

Table 4 Industrial minerals extracted in south-west England

Limestone (Devonian (Devon), Carboniferous (Devon and Somerset), Jurassic (incl. Blue Lias, Forest Marble, and Portland Stone) and Cretaceous (Chalk))
Sand and gravel (Triassic (Budleigh Salterton Pebble Bed), Cretaceous (Upper Greensand), Palaeogene (incl. Aller Gravel) and Quaternary (river terrace and marine))
Sandstone (Devonian (incl. Bude, Crackington and Pilton Mudstone Formations))
Silica sand (Palaeogene, St Agnes Formation)
Igneous rock aggregates (granite (Land's End, Carnmenellis, Bodmin, Hingston Down, Dartmoor), gabbro with basalt dykes (Lizard), dolerite (sill), andesite (lava)). China clay waste (St Austell and Dartmoor Granites)
Building / dimension stone (limestone (Jurassic, incl. Portland Stone, Purbeck Stone, Combe Down Stone, Forest Marble, Osmington Oolite, Blue Lias, Ham Hill Stone), granite (Bodmin)
Slate (Devonian (Delabole, and others incl. Trevose, Tavy, Saltash and Bedruthan Formations))
Peat (Quaternary)
China clay (kaolin) (St Austell and Dartmoor Granites)
Ball clay (Palaeogene (Bovey Formation, Bovey Basin and Petrockstow Basin, Devon and Parkstone and Creekmoor Clay Members, Wareham and Furzebrook))

Figure 2 Part of Moorcroft Quarry, Plymouth (dated 2005). This part of the quarry is now flooded. The present extraction takes place in an extension accessed through the tunnel seen in the upper centre of the photograph.

Industrial minerals in south-west England

South-west England has a diverse and complex geology and is a major region for industrial mineral extraction in the UK. A summary list of the current industrial minerals extracted in south-west England is given in Table 4 (for more details, see Cameron *et al.* 2013). In the recent past, several other industrial minerals have also been extracted, including celestite ($SrSO_4$), fullers' earth, china stone, hematite pigments, and clay for bricks and tiles.

Devonian limestone is extracted in the southern part of Devon, supplying the conurbations of Torbay and Plymouth, and to some extent Exeter, with aggregates (Fig. 2). Jurassic limestone is extracted in Somerset and Dorset (Figs 3, *below* and 4, *overleaf*), where it provides building stone (e.g. Ham Hill Stone; Portland Stone; Purbeck Stone) as well as aggregates. However, the largest area of production of limestone in south-west England is in the Mendip Hills. This is a major producer of limestone for meeting the large demand for concreting and other aggregates in south-east England. Torr Works and Whatley Quarries in the eastern Mendips are two of the largest in the UK, each producing around five million tonnes per annum of limestone products. This is

Figure 3 Quarry in Ham Hill Stone, Jurassic, Upper Lias (Toarcian). Stoke-sub-Hamdon, Somerset (dated 2005).

Figure 4 Cliffs of Portland Limestone, partly quarried away. East side of the Isle of Portland, Dorset (dated 2016).

about 15% of overall limestone production and 6% of total annual aggregate production in the UK. Most of the aggregate products leave these quarries by rail, there being a direct link from the quarries to the mainline to London, using rolling stock owned by the two companies. The quarries are in the Carboniferous Clifton Down Limestone Formation, Burrington Oolite Subgroup and Blackrock Limestone Subgroup of the Pembroke Limestone Group. The limestone was deposited, often as ooids, in shallow seas on platform, shelf and slope areas along with some corals and shelly fauna. Carboniferous limestone makes an excellent crushed rock because it is strong, but compared with igneous rock, sandstone and greywacke aggregate raw materials it is softer and therefore easier and cheaper to extract and crush.

South-west England is one of the world's major producing regions of china clay (kaolin) and ball clay, much of which is exported through the ports of Fowey (china clay), Plymouth (china clay and ball clay), Teignmouth (ball clay), Bideford (ball clay) and Poole (ball clay). Good reviews of the current china clay and ball clay industries are given in British Geological Survey 'Factsheets' (2009; 2011) and in Bristow *et al.* (2002a). The dominant mineral in both china clay and ball clay products is kaolinite. Critically, the atomic structure of the kaolinite differs in the two products. In china clay, the kaolinite has a much more ordered structure, giving crystals that tend to have a good hexagonal shape and a diameter of up to a two or so micrometres across. In ball clay, the crystal

Figure 5 Google Earth satellite image of China Clay extraction area near St Austell, Cornwall. The whitest areas (west, centre and south-east of centre) are locations of current extraction. The off-white areas (lower centre and north-east of centre are china clay pits that have stopped production in the last 10–15 years. St Austell town is in the south-east near the coast.

structure is much disordered, giving smaller, very ragged crystals. The disorder changes the physical properties of the clay, making ball clays much more plastic and therefore more easily moulded compared with china clay. There are very minor impurities of mica, feldspar and quartz (a few per cent only in total), and occasionally a per cent or two of montmorillonite in china clay (Bristow and Exley 1994; Scott *et al.* 1996). In ball clay products, the amounts of mica and quartz can be quite considerable, and there is usually a small amount of organic matter, which also contributes to the higher plasticity. The major use of china clay is in paper, with other uses in ceramics and as a filler or extender in paints. The dominant use of ball clay is in ceramics, particularly sanitaryware, tableware and tiles.

China clay is currently extracted from pits in the central and western part of the St Austell Granite (Figs 5, *previous page*, and 6) and the south-western part of the Dartmoor Granite. Previously it was also extracted from the north-western side of the Bodmin Granite. In the china clay pits the granite is deeply kaolinised (Fig. 7) — that is, the feldspars and to some extent the micas have been variably altered to kaolinite. The alteration process to form the kaolinite is thought to be a combination of hydrothermal activity, which created some mineral veins within the granites and initiated some alteration, followed by deep weathering during the Paleogene (Bristow and Exley 1994; Psyrillos *et al.* 1998). The earlier minerals veins are thought to have facilitated the later movement of meteoric water through the granite. The china clay is extracted where the kaolinisation is most intense, using either high pressure water hoses (monitors) to wash the granite and liberate the kaolinite, or by direct digging and then washing in a processing plant. The china clay product is made by separation of the coarser minerals of quartz, mica, unaltered feldspar, tourmaline and others using a complex system of hydrocyclones and settling in tanks; also sometimes with more sophisticated processes, including bleaching and high intensity magnetic separation.

Figure 6 Wheal Martyn china clay pit with Greensplat pit in background (dated 2005).

Ball clay is currently extracted in south Devon from the Palaeogene Bovey Basin near Newton Abbot and in North Devon, near Torrington from the Palaeogene Petrockstowe Basin. It is also extracted from the Palaeogene clay of the Wareham Basin in Dorset (Bristow *et al.* 2002a). In Devon, both basins developed along a single active strike-slip fault, known as the Sticklepath — Lustleigh fault zone, with sedimentation of the ball clay, associated sands and carbonaceous matter taking place in a flood plain or backswamp environment bordering a river or lake. In Dorset, the clays were deposited in an estuary, where fluviatile and marine influences controlled sedimentation (Bristow *et al.* 2002b). As the quality of ball clay varies both between and within seams, extraction is often on a very fine scale, a sub-seam of only a few tens of centimetres at most being extracted in some cases (Fig. 8, *overleaf*). Processing of the clay is mostly by shredding and blending to create products with the properties required by customers.

Figure 7 Face of abundant quartz tourmaline veins within intensely kaolinised granite (former Bodelva china clay pit). The face is now covered over within the Tropical Dome of the Eden Project.

Some clay also undertakes further processing involving removal of lignite and coarse quartz or drying and milling to make a fine powder.

Conclusion

Apart from oil and gas production, the major extractive industry in the UK is of industrial rocks and minerals. These include many common rocks and minerals, such as limestone, dolomite, igneous rocks, sandstone, sand and gravel, common clay, gypsum and salt as well as a few less common ones such as potash and barytes. In south-west England there is important production of limestone to supply the large markets in south-east England, and china clay and ball clay, much of which is exported.

References

Bristow, C. M. and Exley, C. S. 1994 'Historical and geological aspects of the china clay industry of South-West England'. *Trans Royal Geol Soc Cornwall* **21**, 247–314

Bristow, C. M., Palmer, Q., Witte, G. J., Bowditch, I., and Howe, J. H. 2002a 'The ball clay and china clay industries of southwest England in 2000', *in* Scott, P. W. and Bristow, C. M. (eds) *Industrial Minerals and Extractive Industry Geology*. London: Geol Soc, 17–41

Bristow, C. R., Highley, D. E., Barton, C. M., Cowley, J. F., Freshney, E. C., and Webb, N. R. 2002b 'Mineral resources of East Dorset'. BGS Commissioned Report **CR/01/138N**. Keyworth

British Geological Survey 2009 'Kaolin. Mineral Planning Factsheet'. **www.bgs.ac.uk/downloads/start.cfm?id=1362**

British Geological Survey 2011' Ball clay. Mineral Planning Factsheet'. **www.bgs.ac.uk/downloads/start.cfm?id=1348**

Cameron, D. G., Bide, T., Parry, S. F., Parker, A. S., and Mankelow, J. M. 2014 *Directory of Mines and Quarries, 2014* (10th edn). Keyworth: BGS

CBI 2016 'The UK Mineral Extraction Industry'. **http://www.cbi.org.uk/news/minerals-critical-to-the-uk-economy/cbi-report-the-uk-mineral-extraction-industry/**

Idoine, N. E., Bide, T., Brown, T. J., and Raycraft E. R. 2016 'United Kingdom Mineral Yearbook 2015'. BGS Open Rep **OR/16/021**

Psyrillos, A., Manning, D. A. C., and Burley, S. D. 1998 'Geochemical constraints on kaolinisation in the St Austell Granite, Cornwall, England'. *J Geol Soc* **155**, 829–40

Scott, P. W. 2008 'Industrial minerals in the UK: past, present and future', *in* Walton, G. (ed.) *Proceedings of the 14th Extractive Industry Geology Conference, EIG Conferences*, 1–8; **www.eigconferences.com/2006-proceedings/**

Scott, P. W., and Dunham A. C. 1984 'Problems in the evaluation of limestone for diverse markets'. Proc 6th Industrial Minerals International Congress. *Metal Bulletin Ltd*, 1–21

Scott, P. W. 2011 'The geological setting for industrial mineral resources'. *EMU Notes in Mineralogy* **9**, 13–34 (European Mineralogical Union and the Mineralogical Society of Great Britain and Ireland)

Scott, P. W., Hart, F. W. and Smith, D. 1996 'The quantitative mineralogy of ceramic grade kaolin from the St Austell Granite and its relationship to chemistry and physical properties.' *Proc Ussher Soc* **9**, 91–6

Young, B., *et al.* 2001 'Mineral resource information for development plans: Phase One Cumbria and the Lake District'. BGS Technical Rep **WF/01/02**. (Cumbria, Lake District National Park and part of Yorkshire Dales National Park)

Figure 8 Extraction of individual seams of ball clay within the clay sequence. Preston Manor Quarry, near Newton Abbott (dated 2010).

Tectonic inversion on the Somerset coast

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[edited by David M. Jones, OUGS Proceedings Editor]

[Unfortunately, Dr Anderson was unable to write up his lecture as an article for the OUGS Proceedings*. Therefore, according to our OUGS Symposium lectures policy, what follows is a transcription of Dr Anderson's lecture, made by OUGS Member Michael Grover from our recording of it, the text of which has been edited for readability by the Proceedings Editor. Dr Anderson did not send any of his slides, so, as Editor, I have also tried to indicate where the illustrations were relevant.]*

Dr Anderson's talk was about an often-overlooked aspect of the geology of south-west England: tectonic inversion. It is a subject that brings scientists, and oil company geologists in particular, from all over the world to the north-west Somerset coast, to study some of the structures associated with tectonic inversion.

His talk covered the basic background geology of the area in north-west Somerset, about the broad sense in which he was using the term tectonic inversion, and then what inversion looks like along the coast of north-west Somerset. He then broadened his talk to describe something about the causes of tectonic inversion in south-west England and more generally in the UK.

Showing a map of northern Somerset, Dr Anderson pointed out some of the key components that make up the Variscan rocks of south-west England. There is Variscan basement, which in north-west Somerset is exposed in the Quantock hills and farther west, to the main Variscan exposures of Devon and Cornwall. The main Variscan trend is predominantly east–west, picked out by lineaments shown in satellite imagery; but cross-cut by a series of prominent north-west–south-east-trending structures as well. One such lineament is the Sticklpath-Lustleigh Fault, with the Bovey Tracey Basin and the Petrockstow Basin developed along it.

So, although these lineaments are part of the Variscan make up in south-west England they clearly have a younger, Tertiary history in the Bovey Tracey and Petrockstow basins tertiary history. Dr Anderson then pointed out the post-Variscan cover, shown as 'mucky brown' in a PowerPoint slide [hereafter PP slide]. Locally, it sits uncomformably on top of the folded and thrust Variscan basement. In bore holes, supposedly, you can actually see the unconformable relationship between the basement and the cover. [Dr Anderson showed a slide from a field trip near Thurlsden, Plymouth, of Variscan basement and a 'beautiful' unconformity of the Permo-Triassic deposits resting above them.] These unconformities pass upwardsinto a whole series of Permo-Triassic deposits, relatively flat-lying for the most part, or with low angles of dip. In the case of the Mercia Mudstone Group they pass upwards into the lower Jurassic limestones and shales. In a GSSP of East Quantocks Head, up into the Lias-dominated by black shales and various types of carbonate limestone.

These are the building blocks. And if we look offshore, these Variscan rocks continue, with Permo-Triassic rocks unconformably above them and passing up into Jurassic rocks [pointed out in a PP slide of BGS schematic sections taken from seismic in the Bristol Channel]. passing up into the Jurassic shown in the green colour. There are also Cretaceous and Cenozoic rocks within the Bristol Channel Basin, but there is a significant amount of particularly lower Cretaceous and Upper Jurassic rock missing in the Bristol Channel Basin, suggesting that there has been a hiatus in deposition or an actual up-lift and exhumation. By this I mean removal of overburden and stripping off rock, and then younger rocks being deposited unconformably sometime after the early Cretaceous. This conclusion is based on seismic sections, interpreted as being reactivation of Variscan thrusts: they involve some of the Variscan basement rocks, they shallow off to relatively low dip angles, and they have been interpreted as thrusts that have had subsequent extensional movement, thus developing a series of small rift basins and half-graben sub-basements.

If we then look at the associated structures along the coast — particularly around Kilve and Watchet — there are beautifully exposed normal faults. [Showing a PP slide looking at a fault plane.] Dr Anderson pointed out dip/slip, slicken-fibres dipping north into the Bristol Channel and a whole series of other, smaller structures associated with it, including the relationship between normal faults with relay ramps developed as one fault dying out to a 'tip'; and where they overlap, a relay ramp.

On this small scale (from a few millimetres up to a metre scale) these look relatively unaffected by any later events; they just look like perfect, pristine, normal faults. Nothing else seems to have happened to them since those normal faults were formed.

There are also some prominent north-west–south-east-trending structures. For example, one that bounds the south-west of the Quantock Hills is the Watchet-Copplestone Fault, exposed on the coast at Warren Bay. It is somewhat enigmatic, however, for in the literature it is described as a south-west-dipping normal fault with its Permo-Triassic in the hanging wall dipping towards the fault — in other words with a north-easterly dip. These feartures suggest that some of the Permo-Triassic rocks were deposited in basins associated with extension along some of the north-west–south-east structures; then that the younger Mercia Mudstone Group oversteps these structures, and laps on to the margin of the Quantock Hills, by burying the fault. Where the fault is exposed at Warren Bay the very top of the Triassic are obviously red mudstones. It is unclear as to exactly what these are, but they are possibly slightly older. If we trace the Watchet Fault we can see, if this interpretation is correct, that there is a problem in that we have younger rocks in the footwall of the fault and older rocks in the hanging wall. That is not the typical structure of a normal fault; rather, more the structure and the stratigraphic relationship across a fault, more typical of a reverse fault or quite possibly a strike-slip fault. These structures are not just simple normal faults cutting through the Mesozoic and younger stratigraphy.

To summarise, Dr Anderson showed a PP slide of a cartoon compiled using 'data, originally published by Roberts', showing Variscan compression predominantly north–south, not quite with

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folding and thrust faulting, then the development of Permo-Triassic basins during post-Variscan break-up of Pangea with normal faults; then several phases of extension in the late Jurassic, plus some evidence of either a hiatus or an unconformity in the early part of the Cretaceous, possibly evidence of inversion; and lastly continued deposition in the early Tertiary and a late stage inversion, related to a quite clear compression whose origins are described later.

Thus by 'inversion' I mean structures that were originally contractional thrusts 're-used' as extensional structures, when they are referred to as 'negative inversion'; and when the term is used with then we call it 'positive inversion'. So, what is tectonic inversion? Many rift basins in the Permo-Triassic and younger part of the geological historyexperienced later exhumation through basin inversion. So exhumation is a process by which we strip off overburden, usually as a consequence of uplift and enhanced erosion, although there are also other ways of exhuming rocks. If we look at rift basins we can usually sub-divide the stratigraphy of the rift basin into three main sequences: pre-lift of the Variscan basement; rocks deposited on top of the basement but not controlled by rifting; and then syn-rift parts of the succession deposited during active faulting. When the faulting has ceased we have what is called a post-rift succession being developed. This break-down of the succession is useful in identifying the inversion and the magnitude of the inversion in rift basins. The basin-bounding fault is re-used, and the hanging wall starts to push the syn-rift, in particular, above its starting position (the starting position is often referred to as the null point).

The term 'regional' means a correlative marker between a footwall and a hanging wall. The regional marker extends the footwall across into the hanging wall and for an extensional, or normal fault, the hanging wall drops down below its regional marker, basically a subsidence. In a contractional fault or thrust fault, however, the regional marker extends across into the hanging wall and the rocks above the thrust fault are elevated above the regional marker.

How can we apply this concept to inverted basins?

[Dr Anderson showed a PP slide of a series of cartoons showing various degrees of inversion. He used the cartoons to highlight the syn-rift, and to point out the original configuration before any re-use of the fault, before any offset at the top of the syn-rift, calling this 'a useful marker', or the 'null point']. With different degrees of inversion the null point progressively migrates downward through the syn-rift sequence along the fault, separating areas that are in net contraction — in other words, areas that have been uplifted relative to the footwall and areas below the null point are still in net extension; they have been dropped down relative to the footwall.

If you were to examine the faults up here it would look like a reverse fault, if you were to look at the fault down here it would look like a normal fault [Dr Anderson pointed out locations in the cartoons]. This apparent schizophrenia is one of the characteristics of inverted basins. By the time total inversion is achieved, the base of the syn-rift is matched back up to the equivalent syn-rift maker in the foot wall, i.e. total inversion completely wiping out the original extensional movement with subsequent contractual movement, down and back up.

In summary these are some of the structural characteristics that we might associate with basin inversion: basin-bounding faults or fault complexes, development of antithetic faults, and areas where some of the syn-rift stratigraphy is elevated above regional, while other areas that are below regional have flipped from what looks like reverse structures to normal structures. There is also a characteristic asymmetric anticline developed adjacent to the basin-bounded fault, but typically emergent towards that fault.

This interpretation is all very theoretical, but these observed features are basically what you might expect with tectonic inversion.

How does this interpretation apply to north-west Somerset?

The basin inversion model relies to a certain extent on and includes substantial re-use; in other words the re-activation of the basin-bounding fault. [Showing a PP slide of] a big fault structure at East Quantocks Head, north of Taunton, east of Watchet there are structures beautifully exposed in the beach section. There is a fault with various features suggesting that it has been reactivated. First, the hanging wall: the stratigraphy and thus the age of the rocks relative to the footwall rocks suggest that it is a normal fault — there is a stratigraphic separation of *c.* 35m. However, other features suggest that there has been more to the movement on the fault than just normal movement. If we look at the fault plane we can see multiple slicken-fibres, indicating that there has been more than one slip event. There has also been intense contraction and there is an asymmetrical fold verging towards the fault plane, one of the characteristic features of inversion structures. These structures are effectively little reverse faults or thrust faults developed quite extensively through the hanging wall.

So the concept that basin inversion involves the substantial reactivation of the fault, creating multiple slicken-fibres on it, but not precluding the development of new structures as well — we might expect further contraction as well. [Here Dr Anderson showed a PP slide of a laboratory model used to demonstrate these processes and features.]

Looking again at East Quantocks Head, there is the main fault plane, a dextral strike-slip fault, and, if we look at the relative timing of these features we can see sub-horizontal slicken-fibres, with steps that indicate a dextral sense of movement in the fault.

What is the relative age of this strike-slip fault to the normal faults? At the platform slightly away from the main fault there are some normal fault scarps. They are east–west striking, dipping north into the Bristol Channel. They are cut by the dextral strike-slip fault. A small step in the limestone bedding surface has dropped down — the hanging wall has dropped down to the right. That movement is the equivalent surface of the movement, and the fault scarp is the equivalent to that fault scarp and its dextral offset. There are strike-slip faults that are younger than the normal faulting related to the rifting. Then, looking again at the East Quantocks Head Fault we can see that there is another structure that cuts through, actually terminates the dextral strike-slip fault — it cuts up section to the base of the limestone then runs along and cuts across the main fault plane and offsets it in a thrust sense, moving the top to the right relative to the bottom. Clearly this represents a contracting system. The fault is inverting, but equally developing new structures that cut across it. The thrust fault cuts and offsets the main fault plane.

This process is repeated on several of the bigger faults in north-west Somerset, is not typical of the smaller faults. We do not see any evidence of reactivation along the smaller faults, only on those with tens of metres or more displacement. Another example can be

seen in the Blue Anchor Group, part of the Mercia Mudstone Group [— pointing out in a PP slide] older and younger stratigraphic relationships to the normal fault where there is contractual deformation around it. This is clear evidence that the structures have been re-worked, re-used as contractual structures.

What we have clearly identified is that some of the structures in north-west Somerset have been reactivated, particularly big ones, while the just leave smaller structures remain beautifully preserved as normal faults related to the original rifting.

Why do only some faults reactivate?

One reason is their orientation in relation to the new stress system. In a steep subjected to a very low angle maximum principle compressive stress it is quite difficult to reactive the fault; so fault dip might be one deciding factor.

Similarly, the strike of the structure relative to the direction of later stress might be mis-oriented, such that the fault cannot be easily reactivated. However, there has been much fieldwork done on this in north-west Somerset and there does not seem to be any clear relationship between fault orientation and fault reactivation.

Another possibility is that the bigger faults are the ones that have more fault rocks developed along them because they were the ones that had the biggest displacement along them to start with; large faults are more likely to develop extensive fault rocks, breccias, gouges, etc, and thus they tend to be weaker under the later compressive stress and therefore reactive preferentially.

It might be that the larger faults link to deeper basement structures. So it could be that the bigger faults cut down and actually intersect with the basement where they are linked to pre-existing structures of Variscan origin, and thus also connect to a relatively strong Variscan basin. When these large faults were subsequently compressed the stresses were transmitted through the basement, but only affected the big faults of the cover, were reactivated. Smaller faults sitting within the cover — not linked to the basement — remained passive.

Finally, there is a possibility that larger faults tap into areas that are over-pressured with fluid. We know that fluid dramatically changes the mechanical behaviour of rocks and faults. Perhaps some of the bigger faults tap into areas where there is a lot of fluid can be over-pressured and therefore, under subsequent compression preferentially reactivate.

I want to explore this idea a little bit more, but bear in mind that this is preliminary data, so it comes with a major ‘health warning’.

There are some isotope data taken from carbonates [shown in a PP slide]. They are stable isotopes of carbon ($\delta^{13}C$) benchmarked against a standard, and the same for oxygen isotopes, for different carbonates in different structures in north-west Somerset. The host rocks, typically in limestone beds, have low, relatively light, not particularly negative, $\delta^{13}C$ values. The low values are the benchmark. We are taking as a working assumption that the fluid was sitting in the rocks at the time they were deposited, which was deposited as bedding-parellel veins of fibrous calcite (‘beef’) within the sediments [Dr Anderson was showing a PP slide of fluids within the Blue Anchor Formation and the Westbury Formation, known as ‘shales with beef’ — a common feature of the Lias.] These sediments are a conal structure, in this case with a sub-vertical fibrous character thought to be an early diagenetic feature. They have slightly more negative $\delta^{13}C$, suggesting that a slightly different type of fluid was generated as a result of the diagenesis of the ‘shales, with beef’, a complex interplay, particularly during the formation of organics or with the alteration of organics and hydrocarbons that leads to, or is one of the processes that leads to, the generation of ‘beef’.

These are carbonates associated with mud volcanoes — and so in the north-west Somerset Lias there are domal structures thought to be mud volcanoes. It is in these structures that material has been over-pressured at depth, has risen through the sediment pile and has basically splurged out as a mud volcano. (There are even larger such structures in places like Azerbaijan, at the tens and hundreds of metres scale. The ones in Somerset are only a few metres in diameter.) We sampled the carbonate from their vent tufas and breccias and found that they have a much more negative $\delta^{13}C$ values, suggesting that the fluid coming up from an over-pressured source generated by the mud volcano had a more methanogenic source. This is typical when methane seeps out onto the sea floor as a result of over-pressuring and formation of mud volcanoes — it becomes oxygenated, oxidised and forms an authigenic carbonate with a low, even negative, $\delta 1^{3}C$ value isotopic signature.

Mud volcanoes and diagenetic ‘beef” formation in veins have almost identical $\delta^{13}C$ isotopic values as the host limestone.

Similarly, the slicken-fibres on the normal faults formed with a similar isotopic value range to the veins. Thus, there is nothing to suggest that the early extensional structures formed with any fluid other than the fluid that was sitting in the sediment already. There does not seem to be an external source of fluid, whereas the mud volcanoes do have an external source of fluid.

So, in north-west Somerset, if we look at thrusts, at slicken-fibres on thrust planes, and at reactivated faults where we can clearly see a reverse sense of movement on the reactivated fault plane it looks as if the thrust and reactivated faults are tapping into the same source of fluid or similar source of fluid to the mud volcanoes. I repeat, however, that we are still collecting data.

These data appear to suggest some sort of link between the bigger structures tapping deeper levels, deeper fluid, i.e. the original extensional structures.

What is the evidence that these bigger structures tapped an external fluid source? There are several: the mud volcanoes themselves, based on the isotope data of their breccias and lithic clasts of red mudstone, which suggests that they tapped down into the Mercia Mudstone Group. There are also neptunian dykes (sand ejectites), which are evidence of sand mobilisation and fluidisation — again typically associated with high fluid pressures and veins (in this case gypsum) with sub-vertical fibres in them. This evidence suggests that lithostratic stress was overcome, which is indicative of high fluid pressure to overcome the weight of the overlying rock during the formation of the veins.

I suggest that all of these data, particularly for the Triassic Mercia Mudstone, show that they were over-pressured for a significant period of time. The mud volcanoes seem to be aligned, and there is a north-west–south-east trending alignment in the footwall of the normal fault. So again this evidence suggests tapping down quite deep into big structures.

The next quest is, what caused these processes? I have described the reactivation of normal faults, and the development of strike-slip and reverse faults. Why and when did that occur? To answer these questions we need to understand some of the tectonic boundaries that might have influenced south-west England from the late Mesozoic to the Cenozoic. We can compare the Alpine deformation front, a major collisional plate boundary, and

the spreading systems through the Bay of Biscay; also the mid-Atlantic ridge spreading system and the Iceland plume.

Studies of regional unconformities throughout Britain, and apatite fission track analysis — which gives us some idea of the thermal history of rocks from onshore and offshore in Britain — identify three main periods of exhumation — uplift and removal of overburden: one in the earlier Palaeocene, one later in the Paleogene and one through to the Neogene. Significantly, these studies did not take into account south-west England. There are very little data, but a study of apatite fission track data from north-west Somerset by a Birmingham University PhD student identified broadly similar results to those from elsewhere in Britain, suggesting that we can start applying some of the arguments that effect Britain as a whole to the south-west England and to the Bristol Channel Basin as well.

Setting aside Palaeozoic, because it was mainly post-Variscan exhumation, the early Cretaceous exhumation event affects south-west England with possibly as much as one to three kilometres of rock removal in the early Cretaceous over a significant time period. Such exhumation characterises the western half of Britain.

The exhumation is ascribed to ridge-push associated with the onset of sea-floor spreading to the south-west of Britain, particularly the opening of the Bay of Biscay in the early Cretaceous.

The Palaeogene exhumation episode affects the south-west Britain a bit more patchily, but again there was a significant amount of exhumation, ascribed or related, it is argued, to Alpine compression. Basically, it is suggested that the far-field effect of the Alpine collision was transmitted all the way to the west of Britain, or it was associated with the Iceland plume as it developed in the north Atlantic. Those who support the Iceland plume model believe there is a significant amount of shortening recorded in these structures to account for the amount of uplift. However, it is difficult to calculate the amount of shortening associated with re-activated faults — as I have indicated, some bits are normal, some bits are reversed, so it depends on exactly where you measure the shortening and relies on regional seismic data.

[Pointing to his PP slide, Dr Anderson summed up saying] This is the extent of the Iceland plume head so the British exhumation could be the influence of that; if not, it is associated with stresses being transmitted from the Alpine orogeny.

Finally, Neogene exhumation: the significant Neogene exhumation in the Neogene in south-west England is ascribed to a combination of ridge-push and lithospheric shortening — a combination of ridge-push forces from the emerging Atlantic spreading system and of late Alpine convergence in the Alps.

In summary, there were stress systems associated with each episode of exhumation. Each had a different direction and therefore has a different signature on the reactivated structures in Somerset.

Tellus South West data usage: a review (2014–2016)

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Abstract

The Tellus South West survey was flown during 2013–14 and incorporated two high-resolution airborne campaigns. The first collected radiometric and magnetic datasets and the second acquired LiDAR data. These data are considered high resolution due to the sample density of the remotely sensed measurements. Herein, this paper reviews the recent uses of the Tellus South West data during 2014–2016 for projects that are now completed and for those still in progress. The projects include geological mapping, archaeological surveying, soil mapping, geochemical soil sampling and geothermal energy exploration.

Introduction

Airborne geophysical surveys form a key part of modern mineral exploration projects, but their impact is broadening to a range of other environmental applications (e.g. Young 2016). The large capital cost is offset by the high-resolution sample density and variety of geophysical methods that can be collected during one survey. Modern examples of these airborne geophysical surveys are those of the Tellus Projects in the UK and Ireland, where the airborne surveys were combined with ground-based geochemical surveys of stream sediments and soils. Early priority was given to Northern Ireland (NI), funded by the Northern Ireland government, and to adjacent areas of the Republic of Ireland, supported by EU Interreg IVA funding. Further Tellus surveys are continuing across the remainder of Ireland, funded by the Republic of Ireland government with the aim of completing the entire island of Ireland in a phased programme over several years; the initial target is to complete 50% of Ireland by 2017. In 2013–14, the first phase of the UK airborne surveys was completed over Cornwall and parts of Devon and Somerset, and formed the Tellus South West survey, funded by the Natural Environment Research Council. This coincided with the final phase of the Geochemical Baseline Survey of the Environment (G-BASE survey), which provided near-contemporaneous ground-based geochemical data. All Tellus Projects aim to provide freely available high-resolution data that can support scientific and environmental research, provide an evidence base for regulation and decision-making, and add significant value to regional and national economies. The best documented example of this is from the Tellus Northern Ireland phase, which led to more than £30 million of investment from mineral exploration companies from 2007 to 2012 (www.economy-ni.gov.uk 2017).

In the case of the Tellus South West survey, the data are open-access and managed by the British Geological Survey and Centre for Ecology and Hydrology. The policy provides industry, academia, government and the public with freely accessible data for a wide range of research and innovation activities. Herein, I discuss the advantages of airborne geophysical surveys in the context of Tellus South West and review current and completed projects that use the data.

An overview of airborne geophysical surveys

Airborne geophysical surveys are a key technique in remote sensing and provide important sources of high-resolution data over large areas. The first airborne surveys began with aerial photography from hot-air balloons in the late-19th century. Aerial photography then progressed as part of reconnaissance work during the First World War, when cameras were first mounted on fixed-wing aircraft and airships, and accurate stereoscopic photographs were collected. However, serious advances in the field came after the Second World War with significant developments in both aviation and geophysics.

Post-Second World War, airborne surveys were driven by the need for domestic sources of uranium. This led to the development of gamma-ray scintillometers to sense radiation emitted from uranium mineralisation. Mounting gamma-ray scintillometers and other geophysical instruments such as magnetometers and electrodes (for magnetic and electromagnetic methods) on aircraft made it possible to conduct regional surveys.

Today, airborne geophysical surveys have expanded to incorporate a wider range of geophysical methods. These include airborne gravimetry, gravity gradiometry, LiDAR and multifrequency electromagnetics as well as spectral methods including multispectral and hyperspectral techniques. These newer methods have become possible due to more accurate instruments enabling higher frequency sampling. More classical techniques have also been improved, for example gamma-ray scintillometers have been replaced with gamma-ray spectrometers that can estimate concentrations in potassium, thorium and uranium, and more accurate magnetometers can make measurements three times every second (3Hz) or more. Flying at lower altitude and with closer flight-line spacing also significantly enhances anomaly detection and resolution, and provides better spatial resolution and accuracy.

These modern 'high-resolution' airborne surveys remain a key tool for commercial mineral exploration campaigns, but they also have become a focus for national geological surveys to provide more accurate estimates on the mineral wealth of a country as a way of attracting investment. Many geological surveys collect nationwide datasets funded by national governments or various international funding agencies. The data are usually made available at no cost to the user, to stimulate investment.

Previous data in south-west England

Classical techniques for airborne geophysical surveys include electromagnetic, magnetic and radiometric methods. In the 1950s, using these techniques, the UK Atomic Energy Agency (UKAEA) funded an airborne geophysical survey over Cornwall and Devon. The Atomic Energy Division of the British Geological Survey (formerly Institute of Geological Sciences) conducted the project to identify targets for potential uranium mineralisation. The survey was flown in two phases, at flight lines of 400m (+/- 200m) and at an altitude of 150m (+/- 30m) (Kimbell *et al.* 2003). The first phase over west and central Cornwall in 1957 used all three methods; however, due to a combination of cultural noise and instrument failure, the second

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phase of the survey continued in 1958–59 with just magnetic and radiometric sensors (Kimbell *et al.* 2003). The survey outcomes were not reported at the time due to confidentiality.

The focus of most interest at the time was the airborne radiometric data. An AERE 1444A gamma scintillation counter and a newer AERE 1531A instrument were used during the first and second phases, respectively. Scintillation counters measure the total number of gamma-rays that hit the detector and provide a measure of radiogenic potential of the ground surface. Modern radiometric surveys use gamma-ray spectrometers; however, the 'Total Count' channel records data equivalent to a scintillation counter.

The data were analysed initially by manual contouring. However, to take advantage of advanced spatial analysis tools and Geographic Information Systems (GIS) developed in the 1990s, the British Geological Survey commissioned the digitisation of the airborne radiometric data. The data were digitised from original flight-line records and isorad maps (contoured maps of similar radiation levels), and checked for any previously overlooked features (Kimbell *et al*. 2003). The two phases of the survey were originally considered separately, but the datasets were later merged into one survey using spatial statistics of the gridded data (Kimbell *et al.* 2003). The final gridded data are presented in Figure 1.

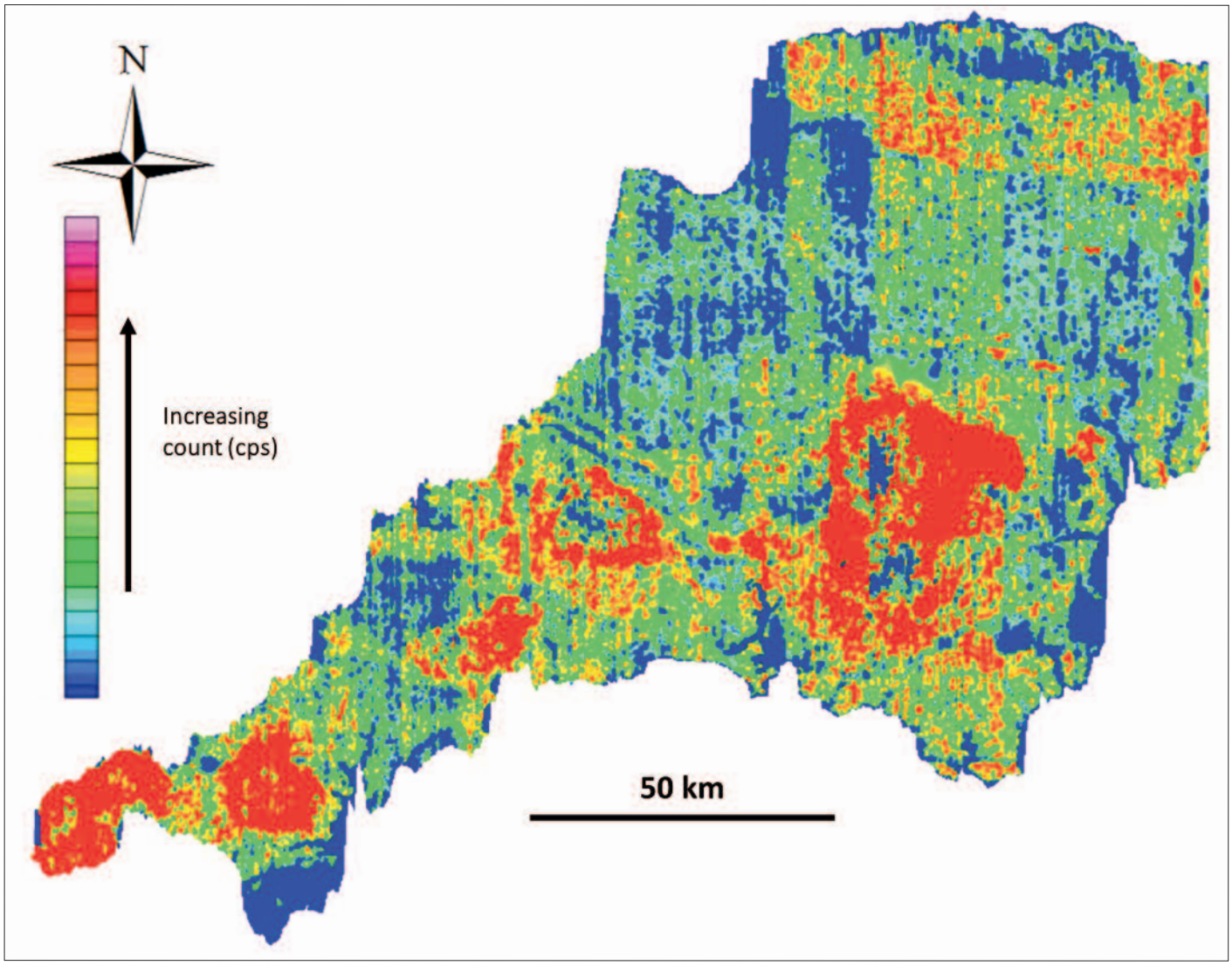
Figure 1 Full extent of the 1950s airborne geophysical survey over south-west England. Originally digitised by Kimble et al. (2003).

The 1950s radiometric survey provided data on key geological features of note in the region, including the Lizard Peninsula, various units within the Devonian and Carboniferous rocks, and the major granite plutons of the Cornubian Batholith. The data successfully identified localised uranium mineralisation, but Kimbell *et al.* (2003) re-appraised some gamma-ray anomalies as the result of anthropogenic activity. These anomalies can be best identified away from the granite margins and correlate with previous mining areas.

This data provided an important digital resource and gave an overall impression of the radiometric variation of south-west England. The digitised data enhanced the regional picture and highlighted the regional geological features. The data have, however, been recently superseded by the airborne radiometric survey from the Tellus South West project. This project collected data at much higher resolution and using a modern gamma-ray spectrometer to inform on the concentrations of potassium, thorium and uranium as well as total count.

Tellus South West

The Tellus South West survey is the first phase of a national geophysical survey (www.bgs.ac.uk, 2017) that will acquire data for priority areas of Great Britain using a range of survey methods tailored to stakeholder needs and the nature of the geology. The area covered by Tellus South West includes the whole of



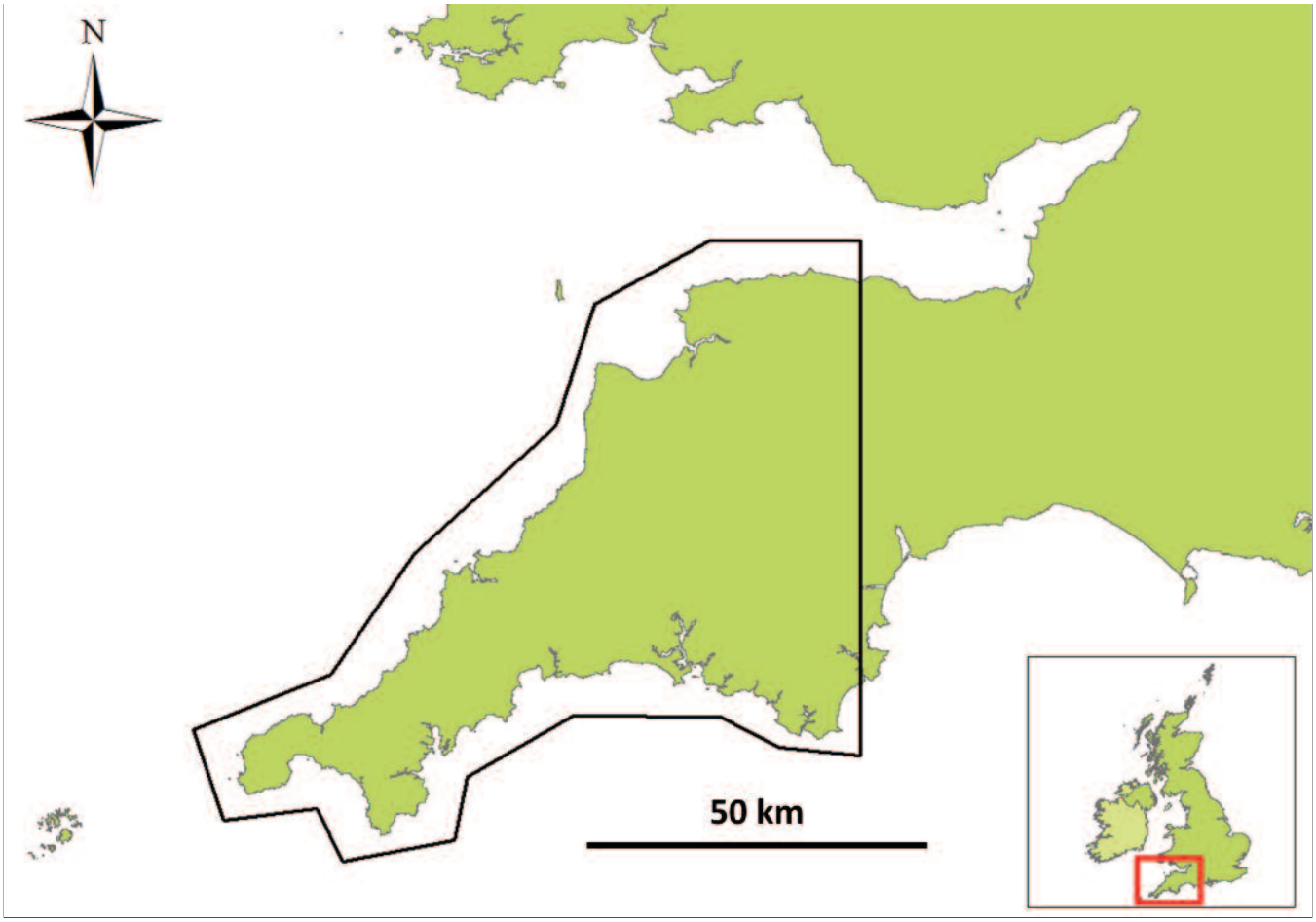


Figure 2 Survey extent of the airborne radiometric and magnetic data from the Tellus South West survey (2013–14).

mainland Cornwall and west Devon and a small area of northwest Somerset (Fig. 2).

The airborne geophysical methods selected for this survey included magnetic and radiometric sensors. The survey was flown from 1 August 2013 to 2 January 2014 (Beamish and White 2014) and managed by the British Geological Survey. A separate LiDAR survey was also flown over the same area during July to August 2013 using a British Antarctic Survey aircraft (Gerard 2014). The radiometric and magnetic survey characteristics are summarised in Table 1.

The airborne radiometric and magnetic survey was flown at an average altitude of 91.6m. An altitude of >244m was maintained over urban areas, and steep topography in some areas forced the aircraft to climb earlier when approaching major hills or cliffs. Artefacts in the data include striping (highlighted in the altimetry) and may reflect different piloting ability (Beamish and White 2014). There is also a strip removed from the dataset over the Devonport area, Plymouth.

Table 1 Survey parameters from the Tellus South West survey for airborne radiometric and magnetic data (flown 2013–14)

survey parameter	*value*	*units*
Line Spacing	200	metres
Line Orientation	North–South	—
Tie Lines	2000	metres
Average Altitude	91.55	metres
Speed	71.21	metres/second
Sample Frequency	1	Hz

The aircraft was mounted with a gamma-ray spectrometer (Exploranium GR820 Console and GPX 1024/256 Detector Packs A+B), which used potassium iodide crystals; and three magnetometers (Scintrex CS-3) were located at the wing-tips and tail. These instruments were calibrated against base stations at Newquay and Cardiff airports to account for diurnal fluctuations. A full open technical report of the airborne geophysical data and processing can be sourced from the BGS (Beamish and White 2014).

The British Antarctic Survey carried out the airborne LiDAR survey and Environment Agency processed the data. The survey produced a highly accurate Digital Elevation Model (DEM), which includes both Digital Surface Model (DSM) and Digital Terrain Model (DTM) products. The data are accurate to 100mm (in both horizontal and vertical accuracy) in areas of no vegetation and limited slope (Gerard 2014). The LiDAR data for the whole region were collected as 4-band LiDAR, meaning the sensor counted the first four reflectors sensed. This level of counting can result in some gaps where ground-returns are not present in the data. The accuracy of the DTM can be affected by dense vegetation due to the on-leaf tree canopy present during summer acquisition. In areas of particularly poor data penetration, ground-returns may be missing and result in a false ground surface (Gerard 2014).

Uses of Tellus South West data

Mapping granites

The granite plutons exposed at surface are poorly understood in terms of evolution and fractionation in relation to the variable granite types observed. This is partly a function of the surface

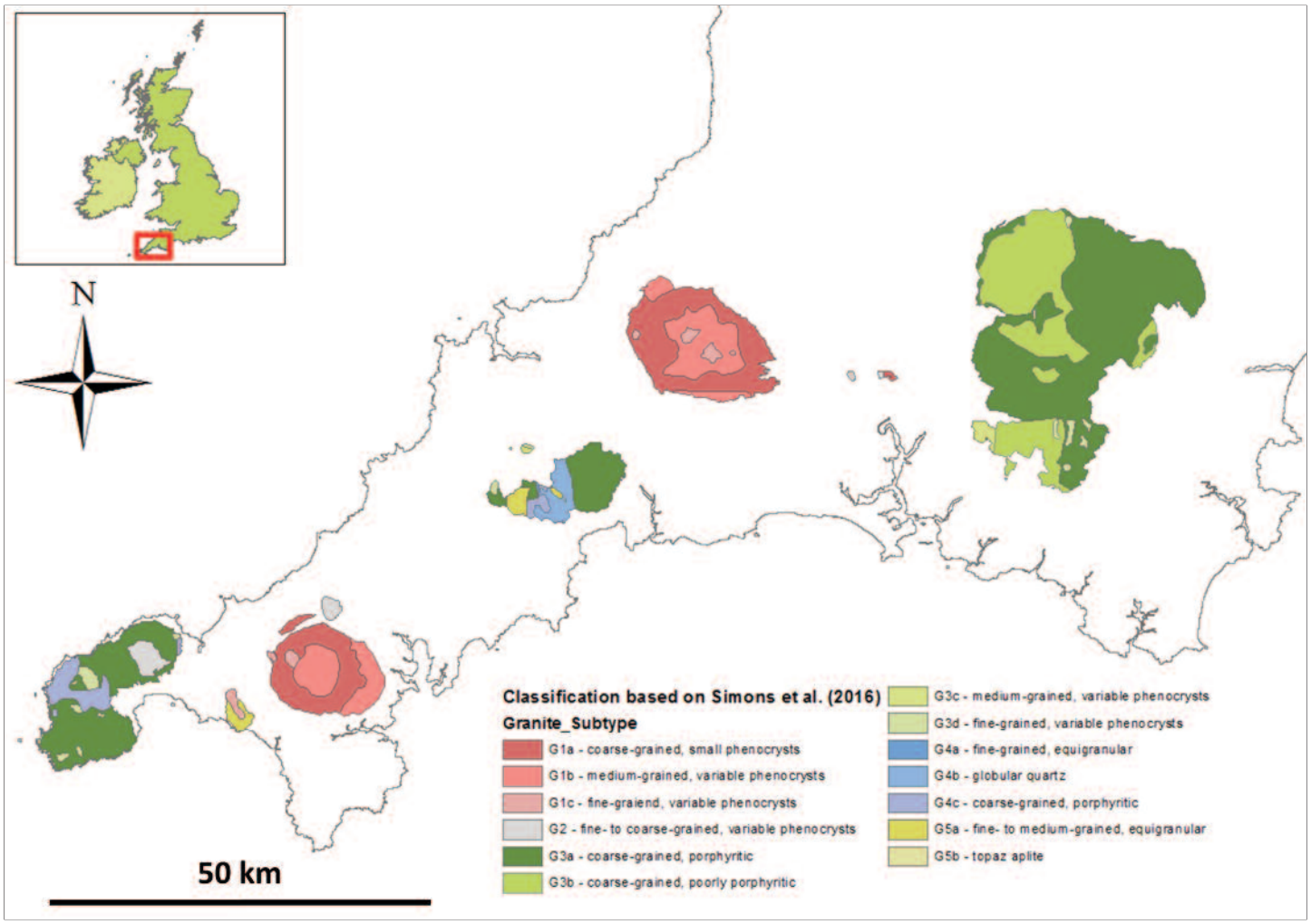

N
50 km
Classification based on Simons et al. (2016)
Granite_Subtype
G1a - coarse-grained, small phenocrysts
G1b - medium-grained, variable phenocrysts
G1c - fine-graiend, variable phenocrysts
G2 - fine- to coarse-grained, variable phenocrysts
G3a - coarse-grained, porphyritic
G3b - coarse-grained, poorly porphyritic
G3c - medium-grained, variable phenocrysts
G3d - fine-grained, variable phenocrysts
G4a - fine-grained, equigranular
G4b - globular quartz
G4c - coarse-grained, porphyritic
G5a - fine- to medium-grained, equigranular
G5b - topaz aplite

Figure 3 Map of the Cornubian Batholith based on mineralogical, geochemical and field relationships (based on Simons et al. *2016).*

outcrop where main inland exposures are limited to granite tors and quarries as well as 'field brash' — large cobble to boulder-grade material, which is assumed to have not been transported far from its source. Spectacular coastal exposures exist around the Land's End and Tregonning-Godolphin granites, although these exposures are exceptional rather than commonplace.

Simons *et al.* (2016) produced the most recent geological map for the granites in the region. This map has updated the previous batholith-wide map used on BGS 1:50 000 maps, which is based on work by Dangerfield and Hawkes (1981). The mapping conducted by Simons *et al.* (2016) drastically improves the understanding through comprehensive geochemical, mineralogical and field studies over the whole batholith. This approach enables consistent data collection and interpretation for each granite and draws together the regional context often overlooked by more focussed studies (e.g. Booth and Exley 1987; Manning *et al.* 1996; Exley 1996). The geochemical data build on work by Stone (1997, 2000) and advances our understanding of how the different granite types relate in terms of evolution and fractionation. The granites are reclassified into five major types (G1–5; Fig. 3), four of which are subdivided into textural subclasses (G1a–c, G3a–d, G4a–c and G5a, b). The G1 and G2 types are two-mica and muscovite granites respectively; G3 and G4 are described as biotite and tourmaline granites, respectively. Both G1–G2 show depletion in Fe, Ti and Mg with increasing Si, while G3–G4 display increasing Rb versus Mg and Li within micas, which suggest these two groups of granites evolved through fractionation. The final G5 type is a topaz granite and considered to be wholly different and formed from a later, biotite-rich restite source. For further information on the relationships of the granites and their source see Simons *et al.* (2016).

The key problem regarding mapping the whole of the granite outcrop in Cornwall and Devon is how to take objective measurements in areas of no exposure. To this end, airborne radiometric data can provide an exceptionally useful tool. The gamma-ray spectrometer records concentrations of potassium (%), thorium (ppm) and uranium (ppm) as well as Total Count (a measure of total gamma rays to hit the detector), which can inform on the distribution of radioelements within the granite. The airborne datasets (including magnetic and LiDAR) are the first to have complete and continuous coverage over the granites.

The distribution of radioelements within the granites indicates variations in geochemistry. For this variability to be interpreted with any certainty, it is necessary to have a basic understanding of the mineralogical hosts of radioelements. For potassium, the potential hosts are many; however, the significant abundance of feldspars (both porphyritic K-feldspar and interstitial plagioclase) and micas provide the main host. Thorium is largely confined to monazites and uranium preferentially enters uraninite; however, this is readily weathered at surface, meaning surface uranium is largely related to zircon and xenotime (Heath 1982; Jefferies 1984; Lucas 1994). The concentration of the radioelements is summarised in Table 2, and is based on estimates found in Dentith and Mudge (2014).

Table 2 Summary of radiogenic minerals and their wt% potassium, thorium and uranium

mineral	*formula*	*Wt% K*	*Wt% Th*	*Wt% U*
Orthoclase	$KAlSi_3O_8$	14.05	—	—
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH,F)_2$	9.02	—	—
Muscovite	$K(Al_2(AlSi_3)O_{10}(OH,F)_2$	9.81	—	—
Monazite	$(Ce,La,Nd,Th,Y)PO_4$	—	4.83	—
Uraninite	UO_2	—	—	88.15
Zircon	$(Zr,U,REE)SiO_4$	—	0–4000 (ppm)	0–6000 (ppm)

Given the unstable nature of uraninite in the surface environment, it may be appropriate to omit uranium data from any classification of the granites. Simple cluster analysis using the K-means unsupervised algorithm can be used to get a basic handle of the distribution of radioelements and create self-similar classes without any *a priori* information. This technique can therefore be used to provide an objective map of the distribution of radioelements, which, given the known mineralogical associations of potassium and thorium, can be used to make geological interpretations. To remove correlated noise from the classification, the potassium and thorium data are converted to sum-normalised data (K/(K+Th and Th/(K+Th)) and the ratio of Th/K is included for relative information on the concentration data. An example from the Bodmin Moor Granite is given in Figure 4.

The example shows how the K-means algorithm captures the distribution of radioelements and groups the data into four classes. These classes fall into two main categories: those where K > Th (Class 1 and 2) and Th > K (Class 3 and 4). In the Bodmin Moor Granite, Class 3 and 4 coincide largely with areas of the G1a subfacies based on Simons *et al.* (2016). Mineralogically, the high thorium reflects the presence of monazite and this is confirmed as an accessory mineral by Simons *et al.* (2016). Class 1 and 2 represent a potassium dominance and are spatially coincident with finer-grained subfacies (G1b, c). These suites are inferred to have comparatively little thorium compared to the G1a subfacies. The divisions of G1 and G2 represent a fractionation series (Simons *et al.* 2016). On this basis, the low thorium areas of the Bodmin Moor Granite may represent an absence of monazite due to fractional crystallisation into the preceding G1a magma.

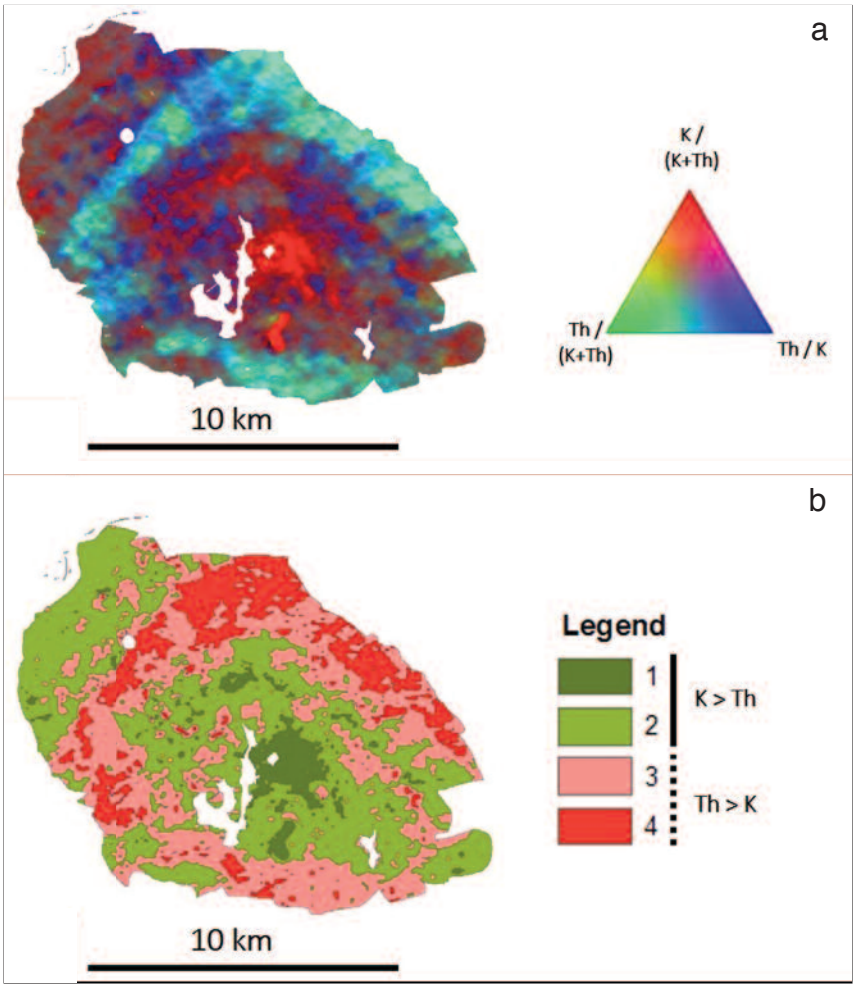
There is potential for re-mapping these granites based on radioelement distributions and improving the understanding of poorly exposed areas. Further work is required to incorporate these ideas into a new geochemical model for granite evolution and fractionation in the area.

Mapping lithostratigraphy and structure

In some areas, the district scale (1:50 000) maps published by the British Geological Survey have not been resurveyed in over a century, while adjacent districts have up-to-date maps based on modern geological mapping and interpretation. The most pertinent discrepancy is between the Plymouth district (BGS Sheet 348) and the Ivybridge district (BGS Sheet 349). The recent development of the Drakelands Tungsten Mine within the Ivybridge district has led to the need for rapid surveying and re-interpretation to modern geological standards. This work is necessary to create an accurate mineralisation model for the deposit, which can drive exploration for further tungsten mineralisation within the region.

The Plymouth sheet (BGS 1998) is described in detail by Leveridge *et al.* (2002). The descriptions laid a foundation for a reinterpretation of the regional structure of south Cornwall and Devon. The remapping and accompanying sheet descriptions inferred a series of E–W-trending Devonian sedimentary basins that show local variability along strike. These basins formed half-graben and graben structures with the footwall forming basinal highs. These highs resulted in the formation of shallow water limestones and localised occurrences of volcanic material. The Devonian basin-high structure was subsequently inverted during Variscan orogenesis and much of the limestone formations upon the highs were either translated northward upon thrust sheets or occluded by overriding nappes. The inverted basins were further deformed by NW–SE-trending apparent dextral fault structures, which offset the basin structure. This structural model has been applied to other recently mapped districts in the region (e.g. the Newquay district; BGS 2012), but some geological districts, including Ivybridge (BGS 1974; surveyed by W. A. E. Ussher in 1899), have not been updated.

Figure 4 Objective map of potassium and thorium distribution in the Bodmin Moor Granite based on K-means classification.



After the completion of Tellus South West, the Tellus How project, a follow up venture to engage local stakeholders in using the data, was set up and brought together workers from Camborne School of Mines (University of Exeter) and Wolf Minerals, operators of the Drakelands Tungsten Mine (Haslam and Howard 2017).

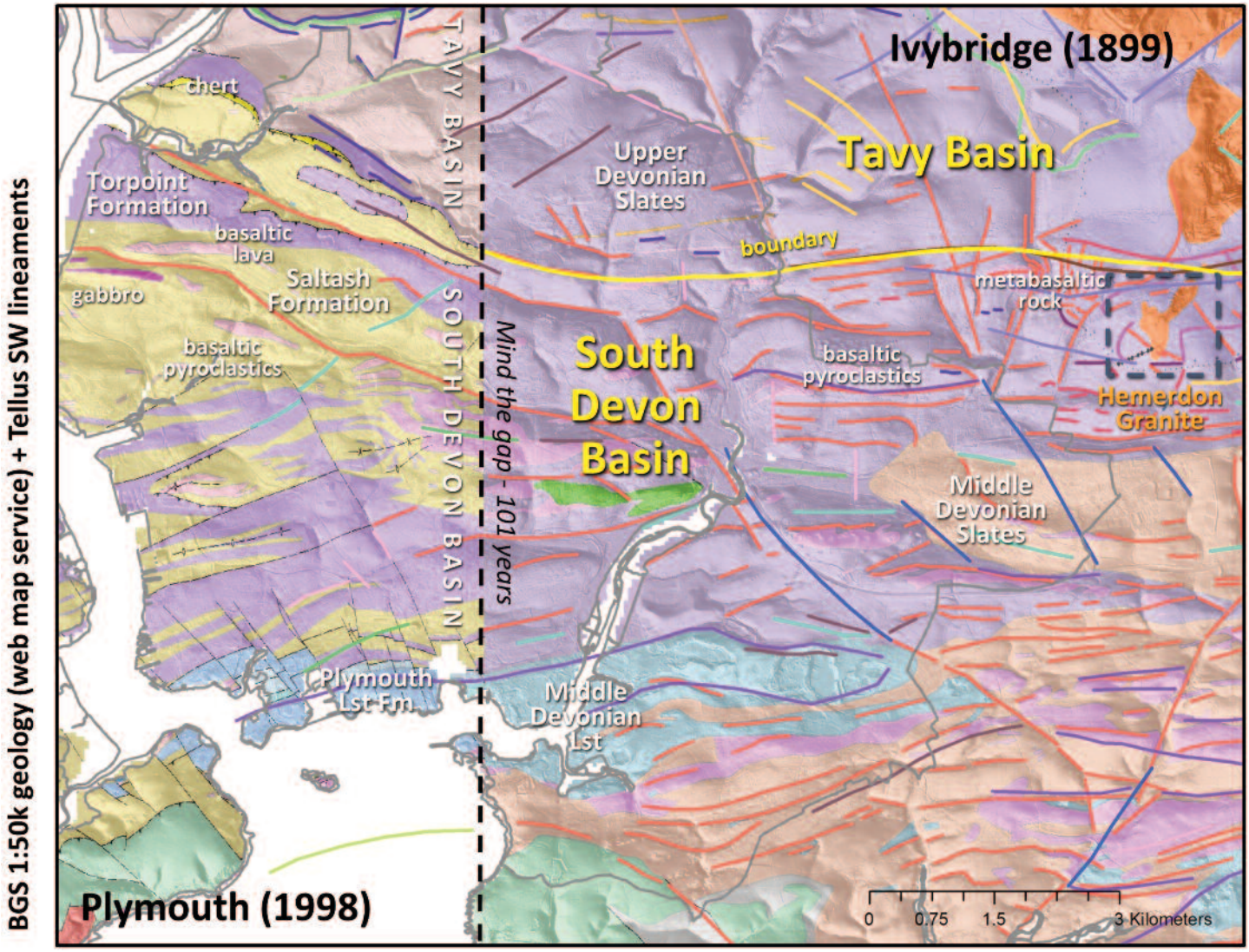
This collaborative project used airborne magnetic, radiometric and LiDAR data from Tellus South West and regional gravity data (BGS Land Gravity Survey) alongside existing mapped geology from BGS. These datasets were incorporated into a GIS for integrated interpretation. Urban areas, particularly the Plymouth area, were only used in limited cases for interpretation due to the perturbation of magnetic and radiometric signatures by anthropogenic artefacts. The magnetic data were reprocessed to calculate the vertical and horizontal derivatives as well as the analytical signal. The radiometric data were manipulated into ratios and relative abundances (e.g. K/(K+eTh+U). LiDAR data was enhanced using a high-pass filter to highlight subtle changes in slope angle (Haslam and Howard 2017).

These reprocessed data were overlain in the GIS using varying transparencies to discern geologically significant lineaments, which either describe a lithostratigraphic boundary or a fault. By overlaying these datasets, indistinct features in one layer may become more obvious when considered with other data displaying similar subtleties.

The magnetic and LiDAR data provided useful information for lineament analysis. Most notable is the continuation of the basinal boundary between the South Devon and Tavy basins, a thrust that occludes the Landulph High, between the Plymouth and Ivybridge districts. Further lineaments were determined from LiDAR data, and in some cases major NW–SE structures in the LiDAR data corresponded with abrupt changes in the radiometric data, which could be interpreted as a faulted contact between two geological units. The radiometric data provided further information and made it possible to correlate some lithostratigraphic units from the Plymouth sheet into the Ivybridge sheet. Of these, the most easily correlated were the comparatively low radiometric signatures of the Plymouth Limestone Formation and minor Devonian mafic intrusive units (Fig. 5).

The Tellus How project re-interpreted the structural geology of part of the Ivybridge district and improved upon the existing lithostratigraphy. Most importantly, the re-interpretation of the area enables the development of a plausible mineralisation model for the Drakelands Tungsten Mine, whereby the later granite was

Figure 5 Reinterpretation of the Plymouth-Ivybridge area. Line-work is derived from analysis of airborne radiometric, magnetic and LiDAR data over the area. Extension of geology from the Plymouth district is based on radiometric responses (Haslam and Howard 2017; permission kindly granted by Dr Robin Shail, University of Exeter).



intruded into the occluded Landulph High. Field studies of the structures seen on the mine site corroborate a likely scenario whereby later reactivation of Variscan structures around the Landulph High created the complex network of vein-hosted tungsten and tin mineralisation (Shail *et al.* 2016; Shail and Simons 2017).

Archaeological mapping

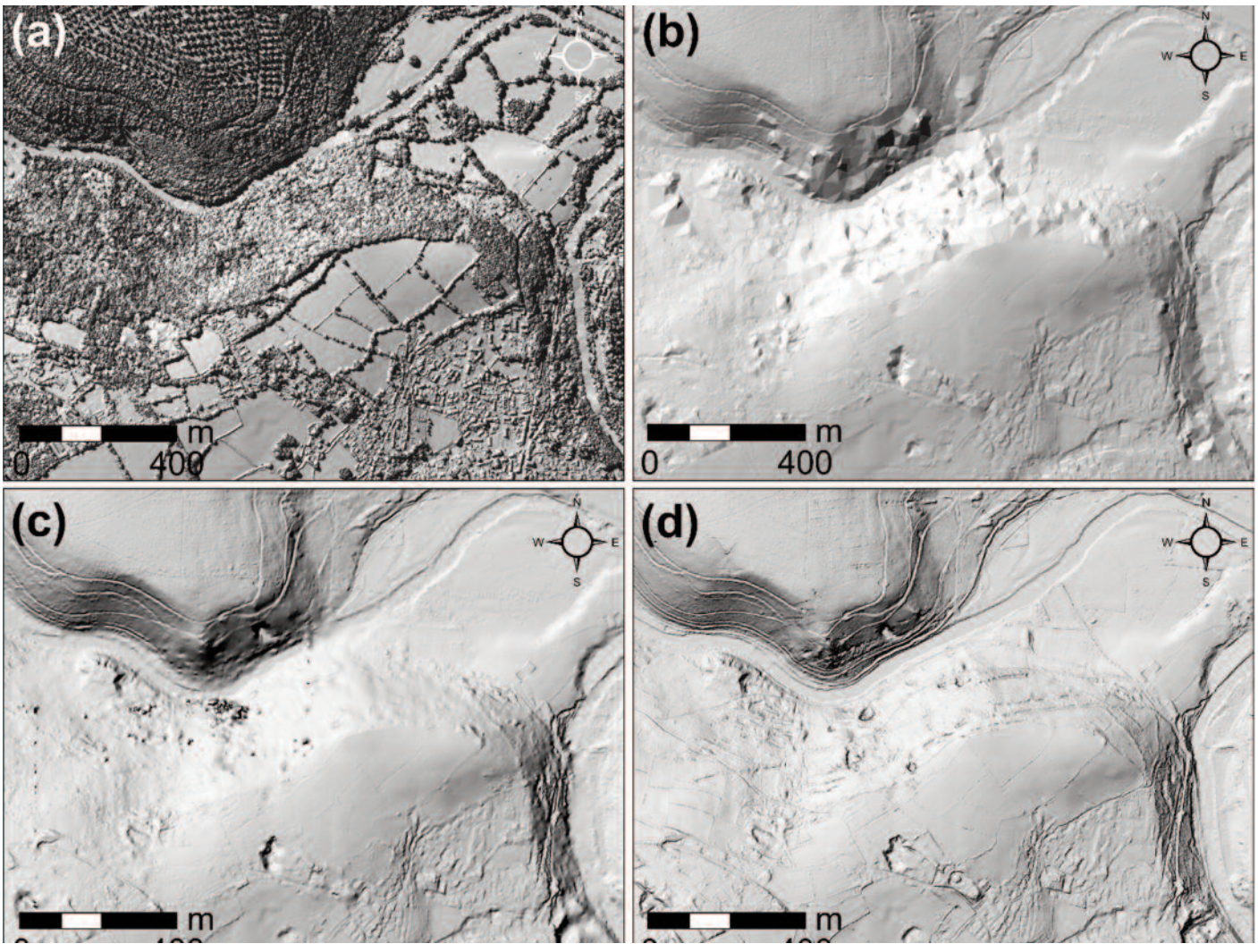
The Tellus How project also conducted archaeological mapping using airborne LiDAR data from Tellus South West surveys. The venture resulted in a collaboration with BGS and Cornwall Council to map subtle or hidden archaeological sites (Haslam and Howard 2017). The use of airborne LiDAR data enabled efficient mapping of large areas while minimising the cost of field surveys. The work targeted burial mounds (or barrows) and historic and recent mine sites for semi-automated archaeological mapping.

The datasets used included both the Digital Surface Model (DSM) and the Digital Terrain Model (DTM) produced from the original LiDAR data, all freely available on the Tellus South West website. The DSM includes information on trees and buildings, while the DTM is processed to remove these details to produce a 'true' ground surface. Both datasets are 1m × 1m pixels, which contain significant detail. However, the DTM data can be degraded in areas of high vegetation. It was necessary for mapping of hidden archaeological features to reprocess the DTM data from the raw LiDAR data to improve these highly vegetated areas (Haslam and Howard 2017). While the DSM and the DTM are highly detailed datasets, a further processing step, known as 'hill-shading', can be applied to help visualise this data. The hillshade algorithm creates a pseudo-3D image of the data by shading the elevation data based on a simulated illumination angle of the Sun. Several different illumination angles can be tested to determine the best visualisation.

The reprocessed and hillshaded DTM was found to be most effective at uncovering hidden historic mine workings, and examples from the Luxulyan and Tamar valleys are shown in Figure 6. These areas are known for historical mines, but many were abandoned before documentary recording of mine plans and locations. This can render some wooded valleys treacherous with unrecorded open pits and shafts. The LiDAR DTM provides an effective tool for finding potentially hazardous mine workings, while minimising the cost of fieldwork to find them.

Further to historic mining works, the airborne LiDAR data can be used to identify burial mounds that may be of archaeological significance. These ancient earthworks commonly have a subtle expression in the landscape, characterised by minor changes in slope, and therefore curvature, of the topography, and can be difficult to pick out with basic hillshaded LiDAR data. To enhance

Figure 6 Example of reprocessed LiDAR data from the Tellus How project. The improved DTM enhances the subtle expression of former mine workings in wooded canopy within the Tamar Valley (Haslam and Howard 2017; permission kindly granted by the British Geological Survey).



the subtle expression of burial mounds, the basic elevation data within a DTM can be manipulated to gain derivatives such as slope and curvature, which measure steepness and roundness, respectively (Fig. 7). Further information can be gained from calculating the surface roughness from a group (or window) of cells as a measure of variability. The Topographic Position Index (TPI), a measure of slope relative to adjacent cells, can also add useful information.

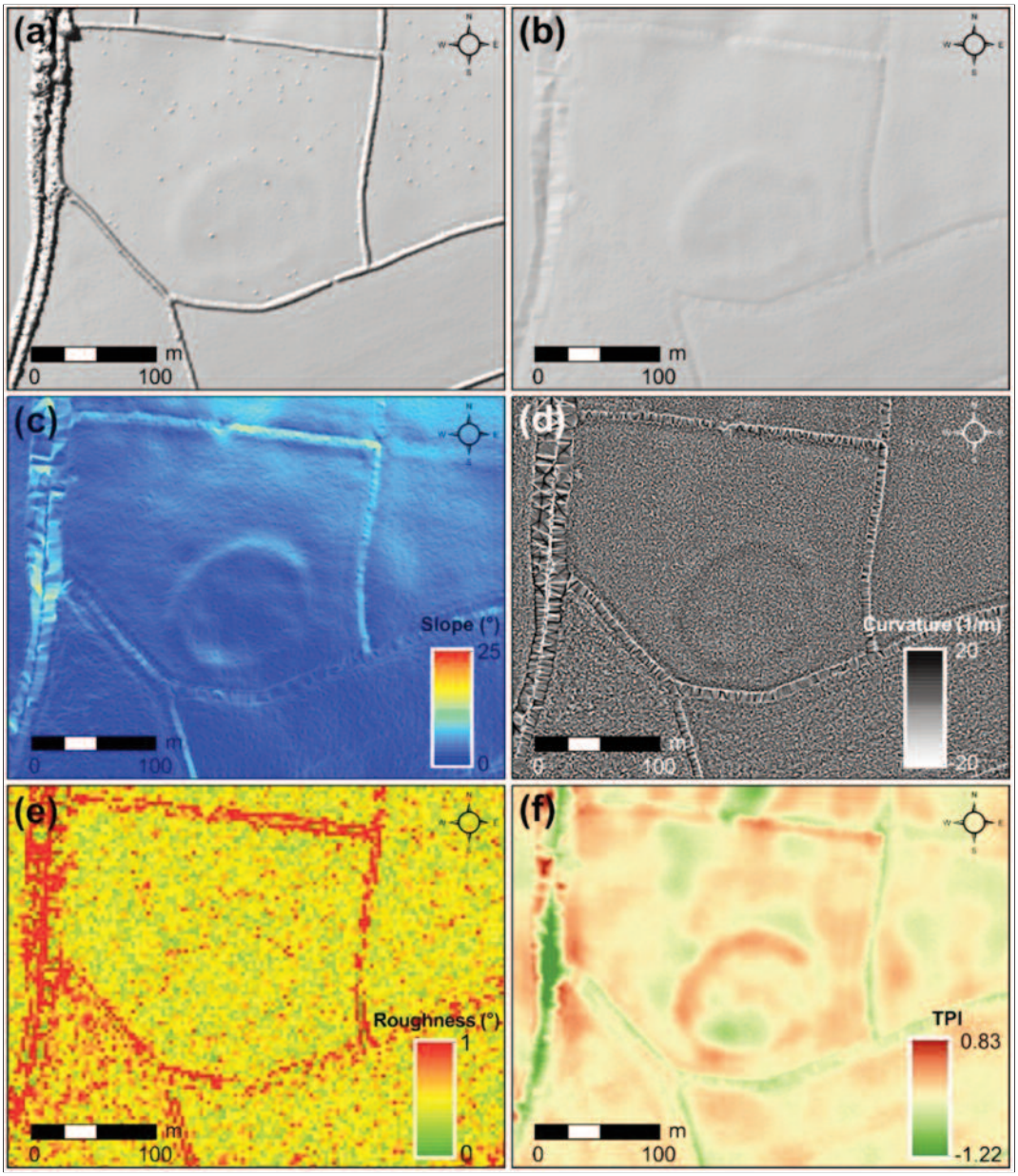
Using a combination of basic GIS functions (Haslam and Howard 2017) can achieve semi-automated mapping of burial mounds. The burial mounds are characteristically circular in plan view, which is a defining feature that stands out most prominently in the TPI data. A subset of the TPI data can be extracted using a threshold and converted from its normal raster (grid) format to a 'shapefile' (vector) format. The shapefile format can then define 'circularity', which is then used to locate and extract circular features, such as burial mounds, from the subsetted TPI data. This method can be employed regionally to rapidly map archaeological features and significantly reduce costs of fieldwork.

Soil mapping

The mapping of soils is important for environmental and engineering studies. Airborne radiometric data can be used for mapping soil type as shown by Beamish (2015). Conventional studies use the radioelement and total count channels to estimate soil type, whereas in south-west England Beamish (2015) uses the attenuation behaviour of airborne radiometric data to inform on the distribution of soil types.

The attenuation behaviour is an important characteristic when considering peaty soils. In the absence of vegetation, soil moisture content and the bulk density of the soil medium control the effect of attenuation on airborne radiometric data. The most prominent areas of attenuation in the Tellus South West data are across the north-west portion of the Dartmoor Granite and the rocks of the Tavy and Culm basins immediately adjacent to the granite on their western flank. Also affected are central areas of the Bodmin Moor Granite. These areas are clearly distinguished in the Total Count channel and ternary diagram (K, eTh, eU) (Fig. 8, *opposite*).

Figure 7 Derived topographic data from LiDAR of (a) hillshade of the DSM, (b) hillshade of the DTM, (c) slope, (d) curvature, (e) surface roughness and (f) Topographic Position Index (TPI) for identifying barrows (Haslam and Howard 2017; permission kindly granted by the British Geological Survey).



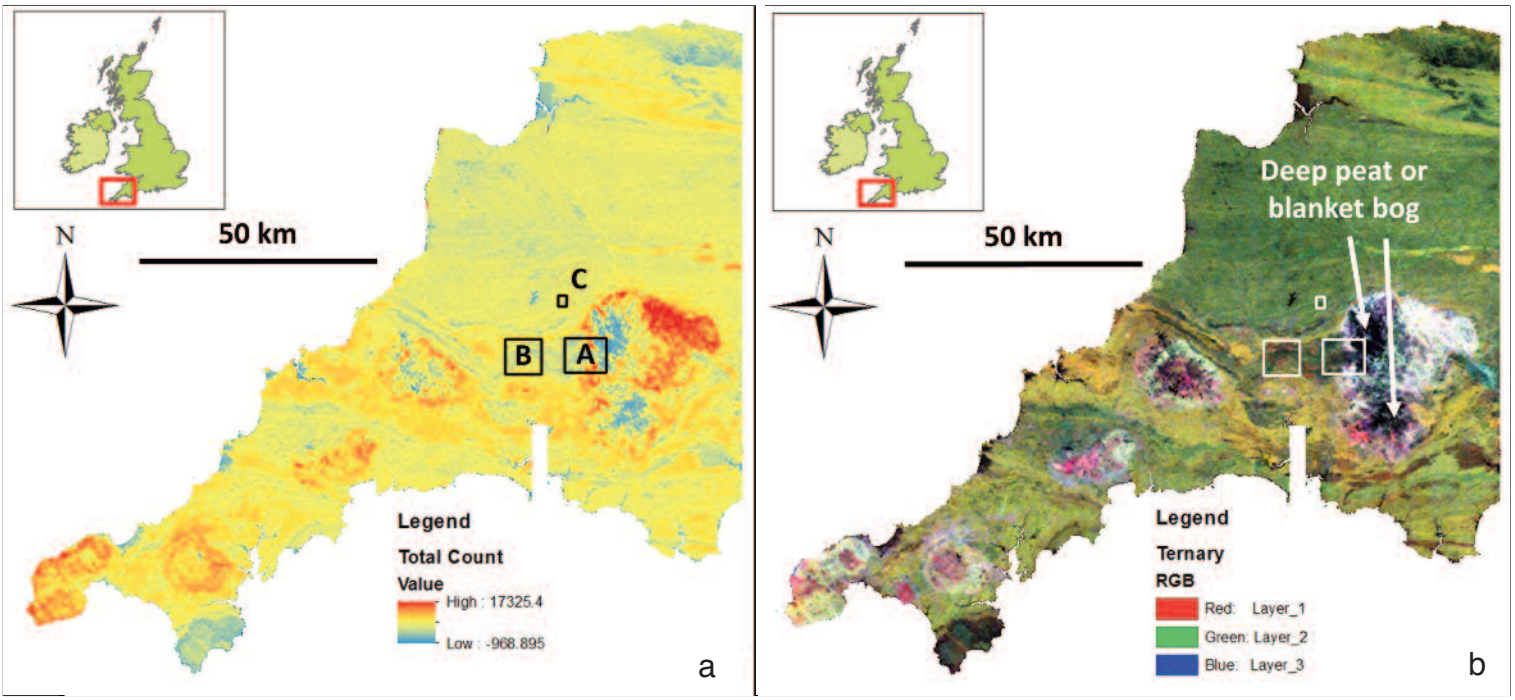


Figure 8 Overview of (a) Total Count and (b) Ternary potassium (red), thorium (green) and uranium (blue) from airborne radiometric data. The sub-areas A, B and C note the studies by Beamish (2015) with respect to attenuation in radiometric data.

Beamish (2015) uses the Total Count channel as a proxy to map peat soils. A threshold of 800cps (counts per second) is applied to Total Count data, which corresponds to known peat occurrences over the Dartmoor Granite reasonably accurately. The 800cps contour can then be used to infer other, previously unidentified, areas of peat based on the Soil Parent Material Database (Lawley 2009) and the Soilscape database. Beamish (2015) identified three areas of potentially misclassified soil types (A, B and C; *see* Fig. 8) using this approach.

By examining areas A, B and C, he further assessed the soil-bedrock behaviour over areas of attenuation. Area A has the highest off-granite level of attenuation. It can be mapped in both aerial photography and on Digital Terrain Model (DTM) data from airborne LiDAR. The area may represent a peat-loam soil wholly contained within the bedrock outcrop of Devono-Carboniferous cherts.

The low Total Count anomaly observed in Area B can be described using a plot of continuous Total Count data, a ternary plot of radioelement concentrations and the mapped bedrock geology. Beamish (2015) demonstrates that high Total Count values in the north and south relate to argillaceous rocks. The mid-Total Count levels are representative of argillaceous and chert sequences, while presumably potassic lavas are shown in pink (>K) in the ternary plot, and intrusive micro-gabbros are coincident with low Total Count and low concentrations of all three radioelements. The low Total Count here is therefore inferred to be characteristic of the bedrock geology and not perturbed by the soil profile. The existing mapping of the Soilscape data supports this conclusion.

Finally, Area C considers the effect of vegetation in the region. Evidently, thick vegetation or woodland with a dense canopy will enhance the effect of attenuation to the gamma-ray signal and Beamish clearly demonstrates this in his example.

Ultimately, the use of airborne radiometric data for soil mapping over the south-west UK is far from elementary. Considerations must be made for bedrock, for known soil type, and for vegetation, all of which can influence the level of attenuation. However, through careful analysis of appropriate combinations of datasets, it is possible to enhance the existing data for mapping of peat soils.

Enhancing geochemical sampling

The Geochemical Baseline Survey of the Environment (or G-BASE survey) is a systematic, nationwide geochemical sampling programme to provide a baseline for future geochemical change in the environment. The survey began in the 1960s and was originally intended primarily for mineral reconnaissance, but applications have since diversified into environmental and medical areas of geoscience (www.bgs.ac.uk 2016). The survey collects soil and stream-sediment geochemical data as well as stream-water geochemical data.

The G-BASE data over south-west England was collected in two phases. A high density, stand-alone survey of the Tamar Valley was conducted in 2002 and the regional continuation of the overall G-BASE sampling campaign was sampled in 2012. To save time and cost, the 2012 sampling programme was optimised geostatistically using a sub-domain approach that characterised the heterogeneity of the geology. This leads, for example, to sparse data points in the soil geochemical datasets for North Devon, but comparatively dense coverage in west Cornwall.

The result of this variable sampling density results in three effective sampling densities for soil geochemistry: the Tamar Valley, North Devon and the remaining areas. This compounds geostatistical analysis, so that classical methods of interpolation are poor tools for predicting geochemical concentrations. The advent of Tellus South West, however, meant that airborne geophysics could be used to help the interpolation of these geochemical data through multivariate geostatistics and machine learning.

Kirkwood *et al.* (2016) used the Random Forest machine learning technique to integrate the airborne geophysical data (radiometric, magnetic and its derivatives) with ground-based Bouguer

anomaly gravity data, satellite Landsat 8 data and elevation data from NEXTMap and its derivatives. For the elements lanthanum (La) and tin (Sn), Kirkwood *et al.* (2016) demonstrate that Quantile Regression Forests, an advancement of the basic Random Forest method (Breiman 2001; Meinshausen 2006) provides a much more accurate interpolation of the geochemical data compared to that of Ordinary Kriging and Inverse Distance Weighting.

The advancement of interpolating geochemical data at the regional scale using the Quantile Regression Forests method is an important step forward in enhancing low-resolution (>100s metres sample density) regional geochemical surveys. The method is, however, heavily reliant on the airborne radiometric data, which may indicate a bias towards certain datasets, and the method requires ground-truthing through field sampling to verify its viability.

Geothermal energy exploration

South-west England is highly prospective for geothermal energy production, and potential resources and extraction methods were investigated during the 1970s and 1980s by the Rosemanowes Hot Dry Rock project (Parker 1999). Areas of high heat flow in the subsurface are considered to be geothermally prospective, and heat flow is enhanced where highly radiogenic granites are present. The principal areas in the UK where this occurs are northern England, eastern Scotland and south-west England (Barker *et al.* 2000).

Continuous coverage of the airborne radiometric data is an important additional dataset for investigating the radiogenic properties of the granites in the region, and for inferring heat production and geothermal energy potential. Heat production is a parameter calculated using the concentration of radioelements based on measurements from the airborne radiometric data and is demonstrated by Beamish and Busby (2016). By calculating the heat production for the whole region and taking a threshold of >5 and >6 $\mu W\ m^{-3}$, Beamish and Busby (2016) could characterise each granite pluton by its heat production potential. These data are summarised in Table 3.

The heat production based on these radioelements can therefore be mapped in a similar way to the original concentration data. These data are, however, affected by variations in soil thickness and properties. Soil cover 'dampens' the calculated heat production, whereas hot-spots occur in areas of no soil cover (e.g. quarries). Beamish and Busby (2016) consider this and apply a correction factor to account for these variations. By applying the correction factor and comparing the results with borehole measurements over the Carnmenellis Granite, Beamish and Busby (2016) demonstrate that the application of their correction factor largely holds, provided different rock densities are used in the calculation of heat production for on- and off-granite areas.

In terms of per cent of total outcrop area >6 $\mu W\ m^{-3}$, the most prospective plutons appear to be the Land's End and particularly Dartmoor granites, although all appear to be prospective at depth (Beamish and Busby 2016). It must also be considered that these measurements are only representative of the surface concentrations of potassium, thorium and uranium based on the airborne radiometric data. The vertical distribution of these radioelements with depth, and therefore the heat production capacity, is wholly reliant on the heat flow estimates and assumes a constant concentration of radioelements.

Summary

I have discussed the broad applications of the Tellus South West airborne survey data. The high resolution of the data makes it desirable, as sampling is often of a higher density than a ground-based sample campaign. The resulting samples can then be interpolated to create gridded data. The airborne radiometric, magnetic and LiDAR data provide an excellent resource and add value to the existing environmental datasets in south-west England. As has been seen in Northern Ireland, such datasets can boost the regional economy and encourage significant investment, which easily offsets the capital expenditure of the initial survey.

The economic benefits of the Tellus South West survey are yet to be seen in full. A rapid expansion in mineral exploration has not been realised. This may be due to the interplay between commodity values and development costs, but datasets such as Tellus South West can certainly help to reduce the perceived development risks, should the value-to-cost ratio become more favourable. Perhaps most importantly, the research projects that have been reviewed herein demonstrate that the data from the Tellus South West survey can be applied and integrated across a wide range of disciplines and applications. The data have potential to enhance mineral exploration projects, as we have seen with mapping techniques and enhancing soil geochemical datasets. However, the data also have applications for environmental and resource aspects, such as soil mapping, social and cultural preservation through archaeological mapping, and development of geothermal energy. Furthermore, the projects discussed here demonstrate the value of using multiple datasets to solve problems. By incorporating a broad range of data where links in physical properties may not be apparent, further information can be gleaned from the spatial correlation and multivariate analyses of these datasets.

The Tellus South West survey has provided the region with a valuable resource. The open-access policy by the British Geological Survey and Centre for Ecology and Hydrology means that the data are freely available to key stakeholders in the region. This policy ultimately leads to research across many disciplines

Table 3 Heat production potential over the main granitic plutons of south-west England (redrawn from Beamish and Busby 2016)

granite	*outcrop (km2)*	*area with Heat Production >5 µW m-3*	*area with Heat Production > 6 µW m-3*	*% total outcrop* area *with Heat Production >6 µW m-3*
Land's End	180.69	72.32	16.33	9
Carnmenellis	138.53	32.34	1.83	1
St Austell	91.27	21.42	4.63	5
Bodmin	203.16	25.85	4.32	2
Dartmoor	624.58	225.62	137.53	22

that will improve our knowledge of the region, and the development of new tools that add value to the data for the wider stakeholder community.

Acknowledgements

I would like to thank Andy Howard at the British Geological Survey for an internal review of the manuscript and his helpful comments; Jon Busby, Robin Shail and Stephen Grebby are also thanked for their comments. Both the University of Exeter and British Geological Survey are thanked for their permission to use figures from a pending report. This paper is published with the permission of the Executive Director, British Geological Survey (NERC).

References

Barker, A. J., Downing, R. A., Gray, D. A., *et al.* 2000 'Hydrogeothermal studies in the United Kingdom'. *Quart J Engin Geol Hydrogeol* **33**, 41–58

Beamish, D. 2015) 'Relationships between gamma-ray attenuation and soils in SW England'. *Geoderma* **259–260**, 174–86

Beamish, D., and Busby, J. 2016 'The Cornubian geothermal province: heat production and flow in SW England: estimates from boreholes and airborne gamma — ray measurements'. **Geothermal Energy 4**, 1–25

Beamish, D., and White, J. 2014 'TellusSW: airborne geophysical data and processing report'. *BGS Open Report* **OR/14/014**

BGS 1974 *Ivybridge. England and Wales Sheet 349*. Keyworth, Nottingham: BGS

BGS 1998 *Plymouth. England and Wales Sheet 348*. Keyworth, Nottingham: BGS, NERC 1998

BGS 2012 *Newquay. England and Wales Sheet 346*. Keyworth, Nottingham: BGS, NERC 2012

Booth, B., and Exley, C. S. 1987 'Petrological features of the Land's End Granites'. *Proc Ussher Soc* **6**, 439–46

Breiman, L. 2001 'Random forests'. *Machine Learning* **45**, 5–32

Dangerfield, J., and Hawkes, J. R. 1981 'The Variscan Granites of south-west England: additional information'. *Proc Ussher Soc* **5**, 116–20

Dentith, M. C., and Mudge, S. T. 2014 Geophysics for the Mineral Exploration Geoscientist (1st edn). Cambridge UP

Exley, C. S. 1996 'Petrological features of the Bodmin Moor Granite, Cornwall'. *Proc Ussher Soc* **9**, 85–90

Gerard, F. 2014 'LiDAR quality control report Project: PM 1478'. *Geomatics* (Environment Agency, National Operations)

Haslam, R., and Howard, A. S. 2017 'TELLUS How — an exemplar approach for end-user innovation and follow up of a major NERC environmental survey project'. *BGS Open Report* [in press]

Heath, M. J. 1982 'Uranium in the Dartmoor Granite: geochemical and radiological investigations in relation to the south west England geothermal anomaly'. Unpublished PhD Thesis, University of Exeter

Jefferies, N. L. 1984 'The radioactive accessory mineral assemblage of the Carnmenellis Granite, Cornwall'. *Proc Ussher Soc* **6**, 35–40

Kimbell, S. F., Cooper, D. C., and Scrivener, R. C. 2003 'The digitisation and geological interpretation of data from the 1957–9 airborne radiometric survey of south-west England'. *Geosci S-W Engl* **10**, 410–16

Kirkwood, C., Cave, M., Beamish, D., *et al.* 2016 'A machine learning approach to geochemical mapping'. *J Geochem Explor* **167**: 49–61

Lawley, R. 2009 'The Soil parent material database: a user guide'. *BGS Internal Repor*t **OR/08/034**

Leveridge, B. E., Holder, M. T., Goode, A. J. J., *et al.* 2002 'Geology of the Plymouth and south-east Cornwall area'. *Memoir of the British Geological Survey, Sheet 348*

Lucas, F. W. A. A. 1994 'The distribution of uranium and thorium in the Cornubian Batholith'. Unpublished PhD Thesis, Camborne School of Mines, University of Exeter

Manning, D. A. C., Hill, P. I., and Howe, J. H. 1996 'Primary lithological variation in the kaolinized St Austell Granite, Cornwall, England'. *J Geol Soc London* **153**, 827–38

Meinshausen, N. 2006 'Quantile regression forests'. *J Machine Learning Res* **7**, 983–99

Parker, R. H. 1999 'The Rosemanowes HDR Project 1983–1991'. *Geothermics* **28**, 603–15

Shail, R. K., McFarlane, J., Hassall, L., *et al.* 2016 'The geological setting of the Hemerdon W-Sn deposit', *in* 40th Annual Winter Meeting of the Mineral Deposit Studies Group, 2016

Shail, R. K., and Simons, B. S. 2017 'Tectonic and structural controls on the genesis and emplacement of early two-mica (G1) and muscovite (G2) Cornubian granites and their associated W-(Sn) mineralisation', *in* Ussher Society 2017 *56th Annual Conference of the Ussher Society: Geoscience in South-West England, 2017*

Simons, B., Shail, R. K., and Andersen, J. C. Ø. 2016 'The petrogenesis of the Early Permian Variscan granites of the Cornubian batholith: lower plate post-collisional peraluminous magmatism in the Rhenohercynian Zone of SW England'. *Litho* **260**, 76–94

Stone, M. 1997 'A geochemical dichotomy in the Cornubian batholith'. *Proc Ussher Soc* **9**, 206–10

Stone, M. 2000 'The early Cornubian plutons: a geochemical study, comparisons and some implications'. *Geosci S-W Engl* **10**, 37–41

Young, M. (ed.) 2016 'Unearthed: impacts of the Tellus surveys of the north of Ireland'. *Royal Irish Academ*y www.bgs.ac.uk (2016) G-BASE' [online]. **http://www.bgs.ac.uk/gbase/gBaseSW.html** (accessed 7 January 2017)

www.economy-ni.gov.uk (2017) 'Tellus Project Findings and Legacy' [online]. h**ttps://www.economy-ni.gov.uk/articles/tellus-project-findings-and-legacy** (accessed 7 January 2017)

www.bgs.ac.uk 2017 'National Geophysical Survey' [online]. **www.bgs.ac.uk/research/energy/NationalGeophysicalSurvey.html** (accessed 7 January 2017)

Book review

Fossen, Haakon 2016 *Structural Geology* (2nd edn). Cambridge University Press (978-1-107-05764-7; hardback, 510pp; £49.95)

This is a remarkable book. Unlike the numerous (and ageing) structural geology books on my shelf, this book is modern and bright, with clear text and copious diagrams and photos. It grabs your attention right from when you first pick it up.

The photographs are simply stunning. These depict world-class examples of the structures being described, many of which are from the Caledonides of Fossen's native Norway and so have a certain resonance with our native geology north of the border. Each chapter begins with a page giving a rationale for the coming section, along with a full-page image of a relevant, awe-inspiring geological location. With 22 chapters, totalling more than 500 pages packed full of photos and figures, there's plenty to please the eyes.

But despite the beautiful photography, Fossen's book is not casual dip-in-and-out coffee-table fodder. This is a serious textbook, and demands devoted study. If you are suffering withdrawal symptoms after finishing your OU studies (as I was) then *Structural Geology* may provide you with an academic fix.

After a short introductory chapter, the book gets straight into the meat by setting up the theoretical background of stress, strain and the strain ellipse. For many, this will be a dry start, but the concepts introduced here are referred to again and again throughout later chapters. Some elementary linear algebra is expected here (and less elementary — I would wager few geologists will know how curl is defined), but if mathematics is not your strong suit you may get by with the basics and taking some things at face value. Being by first degree a physicist, I found the mathematical framework illuminating.

In these early sections of the book, terms are often used before they are defined. In nearly every case, there's no need to worry, as the term is explained within a page or two, but I suspect there's been some rearrangement since the first edition that has left these unintended forward references.

The bulk of the book works through a thorough treatment of rheology, joints and veins, faults, palaeostress, microstructure, fabrics, lineations, boudinage and shear zones. Deformational structures are generally treated independently from tectonic regimes, providing the understanding required to interpret field evidence in isolation before building up the big picture. These chapters often explained things that I'd often wondered about, or introduced me to new phenomena that I was eager to look for in the field, giving the book a certain 'ah!' or 'wow!' factor.

A persistent theme of the book is scale. Many phenomena look similar at vastly different scales, while in contrast sometimes a deformation can be considered plastic at one scale while brittle at another. This focus is insightful, though the short aside reducing back-arc spreading to simple boudinage of the crust seemed to be stretching the analogy a little too far for me.

The book then turns to tectonic regimes, to put things into context — an approach perhaps more reminiscent of our much-loved S339. This section of the book covers extensional and compressional regimes, as well as transtension and transpression, and includes an interesting chapter on salt diapirism. As throughout the whole book, Fossen's petroleum industry background informs many of the examples, but I never felt the book stinted on phenomena related to non-oil-bearing settings. The final chapter dips into how structural geology relates to metamorphic petrology and how together they can shed light on polyphase deformation. Two appendices cover the deformation matrix in more detail, and spherical projections.

An extensive glossary is not forgotten, and as is no doubt compulsory for any textbook today, there are online resources and software to give practice in the concepts introduced. Figures from the book can be downloaded, along with additional photos. Each chapter has an associated detailed slide deck that covers the material in the chapter. End-of-chapter questions also have answers on-line, but these are only available to lecturers.

This is not a cheap book, but it is a superb resource if you are willing to dedicate the time to in-depth study.

— Michael Perkins, BSc, PhD (Dunelm), BSc (Open)

The use of archaeological and historical data in interpreting river evolution: a case study from the Exe Valley, Devon, UK

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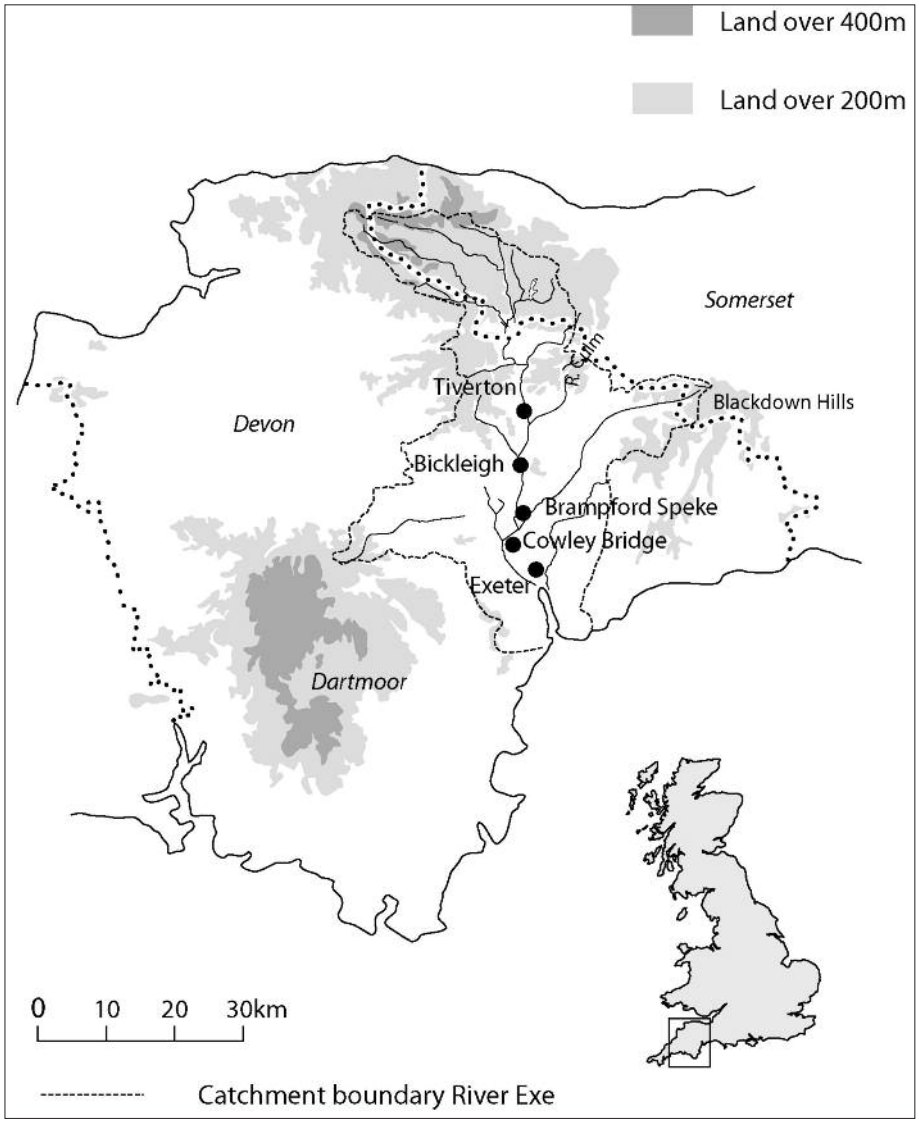
Introduction

In contrast to the previous talks [at the Exeter OUGS Symposium] that looked at long periods of time and the 'big picture' of earth movements, this article will consider a very short period of geological time and a constrained area; but many of the conclusions have wider implications. The location is the Exe Valley in Devon and the timescale covered is the Late Glacial and Holocene (from *c*. 25,000 yrs ago to the present), focussing on the distribution and changes of Holocene channels on the Exe floodplain. The need for understanding of river behaviour in modified floodplains is important due to the large areas of land involved — *c.* 1 million hectares in 2011 (UK National Ecosystem Assessment 2011) and increased extreme weather events. Access to the archaeological reports produced by Exeter Archaeology and to material held by the Devon Heritage Centre has added useful data to the picture of river changes over this period.

Figure 1 The Exe Valley, location and topography.



The River Exe

The River Exe is unusual, as it is a lowland river that drains uplands, rising on the high ground of Exmoor and draining part of Dartmoor and the Blackdown Hills (Fig. 1). The valley forms are bedrock governed with wider valleys of up to a kilometre wide occurring on the softer, more easily eroded Permian rocks and constricted valleys of *c*. 400m wide on the much more resistant Carboniferous material (Fig. 2, *overleaf*).

The south-west of England has high rainfall compared to the rest of Britain (regularly up to 1,800–2,000mm a year on the higher ground of Exmoor and Dartmoor), and the combination of this high rainfall and the relatively impermeable bedrock results in a rapid response downstream to rainfall on Exmoor, recorded by flow gauges in the Exe Valley within hours of heavy rainfall. This is seen in particular at the village of Bickleigh, which is situated at the southern end of a constricted reach (Fig. 3, *overleaf*), and farther downstream in the Exeter basin; hence the need for major flood defences and the current plans to upgrade the present overflow channels.

The floodplain deposits in the valley consist typically of silts of varying thicknesses (0.3–1.5m) underlain by gravels of local material (Edwards and Scrivener 1999). The change to silt sedimentation is likely to be a response to changing conditions upstream and much of this was probably due to human influences. There is evidence from microlith finds along the Exe Valley for an important Mesolithic summer hunting route following the Exe Valley northwards to Exmoor (Silvester *et al.* 1987), and further evidence of Roman and earlier mining on Exmoor at Roman Lode and Anstey's Coombe (Brown and Bennett 2009). Mining activity and related forest clearance for firewood or for ease of access to pits will have affected sediment supply downstream, freeing-up finer material for erosion.

Dated river terrace deposits in the Exe Valley (Brown *et al.* 2010) show that the Exe flowed in the Pleistocene, so the river would have been affected by the rapid climate changes that occurred through the Late Glacial period to the Holocene, and the classic 'underfit' streams present in the wider valleys are likely to be the result of higher flow regimes in the past. Other evidence of change in fluvial behaviour includes remains of older channels (palaeochannels) that can be observed in aerial photographs and traced on the ground, particularly when flooding highlights their positions as they refill. Field walking, geomorphological mapping and

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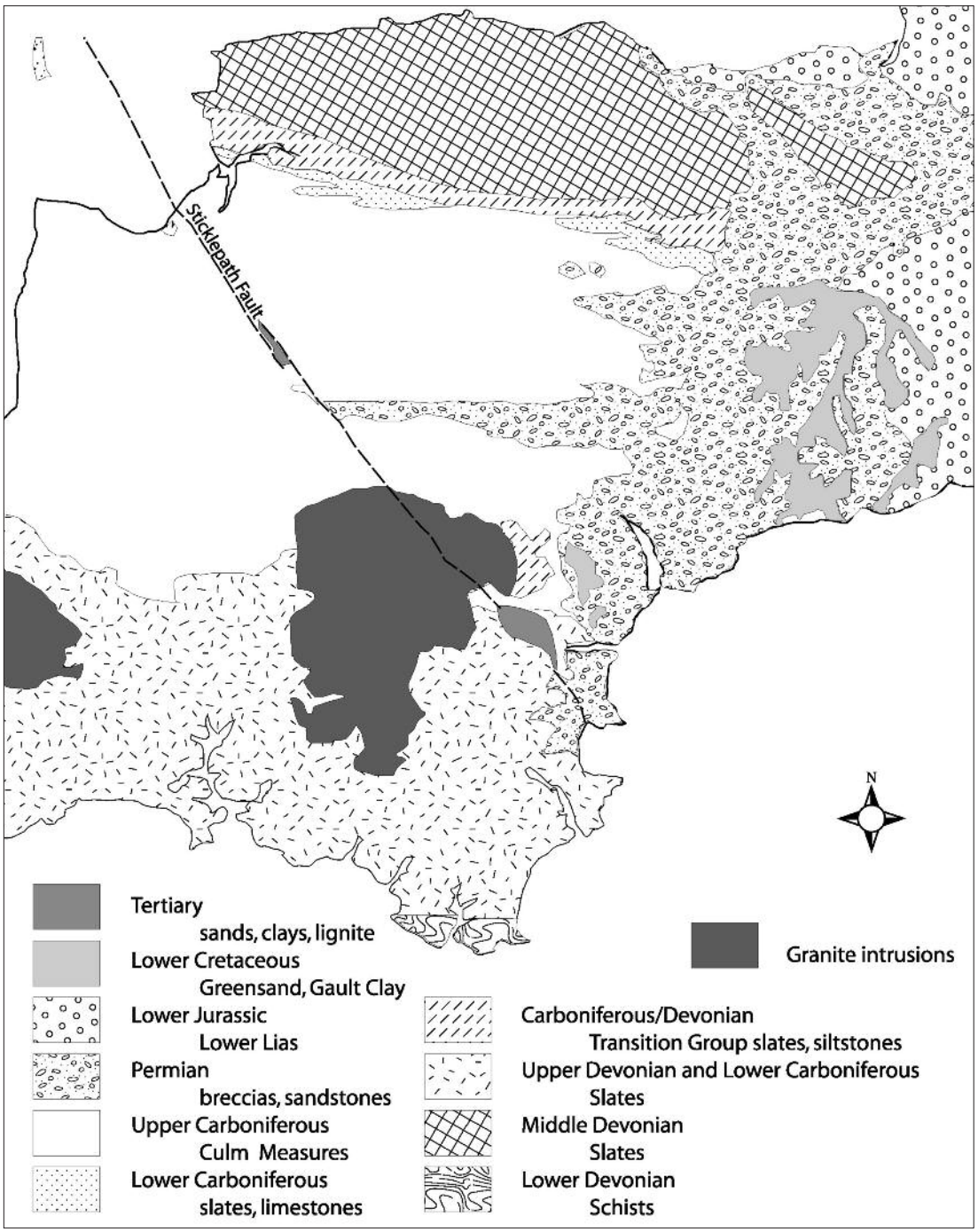


Figure 2 The geology of Devon.

Figure 3 Bickleigh Bridge, showing flow in summer (left) and after autumn rains (right).

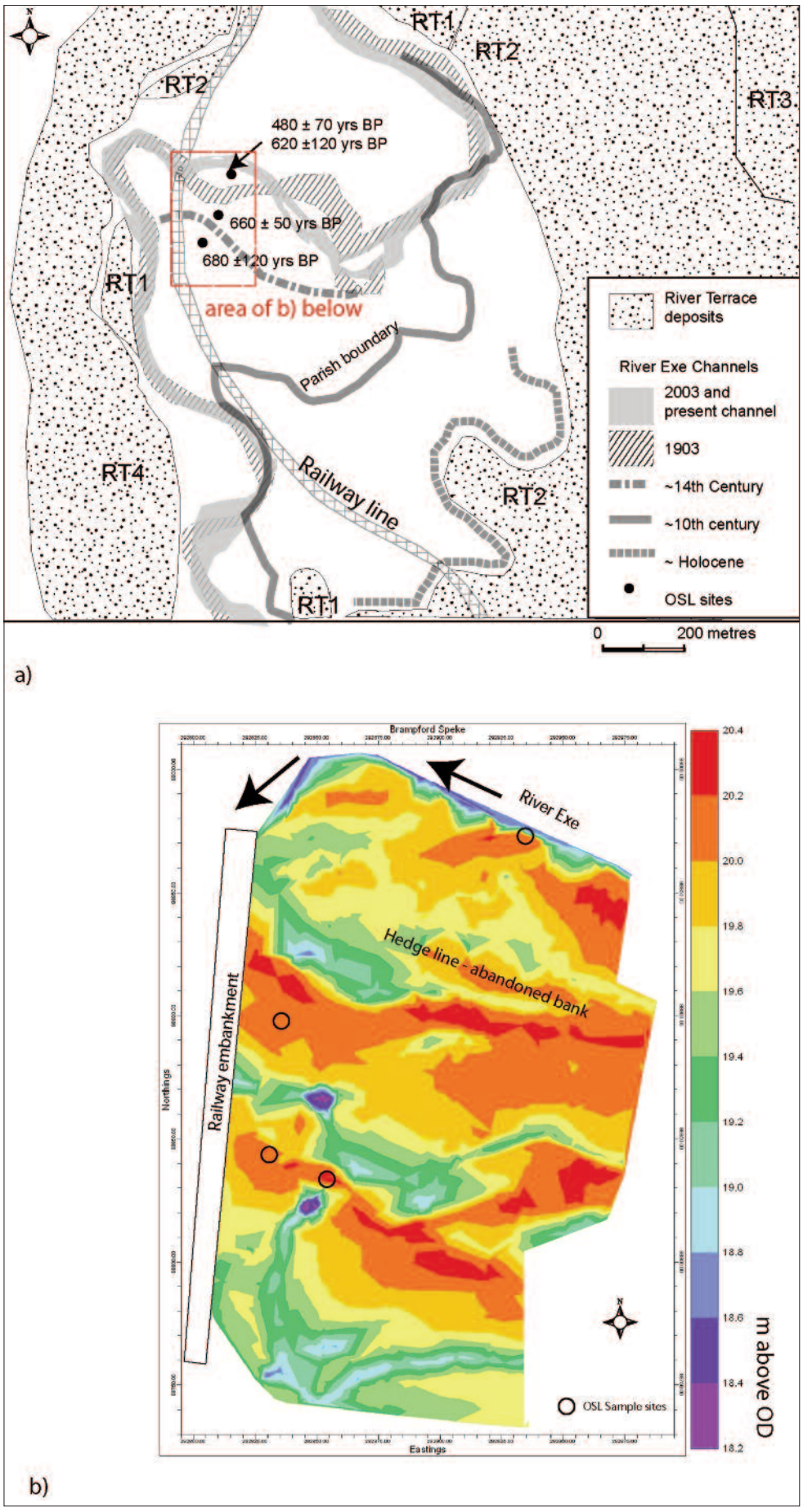


Figure 4 (a) Brampford Speke geomorphology and major palaeochannels; (b) Digital elevation Model of area marked in Fig. 4a. Colours indicate height above Ordnance Datum, blue lowest.

ground-penetrating radar surveys built up a history of river behaviour on the floodplain, with the majority of the evidence found in the wider basins rather than in the constricted reaches (Bennett 2005). This study looks at two contrasting basins: Brampford Speke and Exeter.

Brampford Speke

The 1km wide basin at Brampford Speke is about 6km north of Exeter and sited on the Dawlish and Shute Sandstones of the Permian and bounded to the north and south by narrower constricted valleys sited on Carboniferous Crackington Formation bedrock. The river forms a large loop as it flows south and the area is an SSSI for fluvial geomorphology (Gregory 1997). There is a sequence of river terrace deposits on both sides of the valley and the village itself is situated on the higher ground of RT4 (River Terrace 4 in the BGS nomenclature) well clear (*c.* 10m) of the floodplain. From the pattern of terrace deposits there appears to have been a gradual westward shift of the riverbed from RT4 to RT2; RT1 is less clearly defined (Fig. 4).

The valley floor here has been subjected to little human modification apart from the emplacement of the Exe Valley Railway that ran north–south along the valley, which was dismantled in the 1960s leaving embankments and bridge piers. The piers have affected flow, causing oscillation of the river upstream. A striking example of this is the line of an abandoned river bank shown in Figure 4b along the route of the 1903 channel that has had implications for land ownership — the present riverbank moved north in one of these oscillations, and apparently this has not as yet been reflected in the Land Registry records.

There are traces of abandoned channels on the floodplain, as well as two large pools that are in hydraulic continuity with the river, filling as water levels in the river rise. At the southern end of the basin there is the trace of a distinct 2–3m wide shallow palaeochannel that unfortunately no longer has any datable sediment in it. Aerial photographs show many palaeochannels, so, after field walking to check further, a map of channels on the floodplain was produced (Fig. 4a).

At this stage any evidence that could constrain the ages of the various features was used; for example, Brampford Speke has an Anglo-Saxon charter and inspection

of older maps shows that the line of the parish boundary follows a major palaeochannel, suggesting that this channel was active at the time of fixing boundaries sometime around the 10th to 13th centuries. Another channel runs along the floodplain following the edge of RT1, suggesting an age of Late Glacial to Holocene. In the south of the basin a palaeochannel trace runs along the edge of RT2 and so has been interpreted as an early Holocene channel. There is also archaeological material in the valley that constrains ages, including a Neolithic barrow on RT2 showing that RT2 must predate the Neolithic.

The dominant channel processes here were described by Gregory (1997) as being controlled by flows with a return period of 2–5 years, an important fact, as larger flows with higher return periods are less erosive because the excess energy is dissipated in inundation of the floodplain. Research by Hooke (1977) into bankside erosion and channel changes over the last 200 years on the site used tithe maps, Ordnance Survey maps from between 1887 and 1962, and surveying to reconstruct a sequence of bank positions. Hooke's work showed a steady rate of erosion over a period of about 200 years, but this pattern is not reflected in the older channels. A differential GPS survey on a metre grid covered the area shown in Figure 4 as the expected pattern of 'slip-off' slopes towards the river did not seem to be present. The survey showed that the ground is in fact all at a similar height, but is dissected by palaeochannels crossing the floodplain. The implications of this are that the river is not in fact meandering, but is rather switching channels, and this seems to happen in particular places known as 'avulsion nodes' (Bennett *et al.* 2011).

Finally, Optically Stimulated Luminescence (OSL) dating was carried out on sampled silts from immediately above the gravels, selecting sites on either side of one of the large palaeochannels and from a section in the present river bank. The choice of dating method was constrained as there is no datable organic material present due to the very acidic groundwater. OSL will provide a date for the last exposure that sediments had to light, so is a useful indicator of the timing of burial. To be most useful, the samples were taken from as close to the bases of channels as possible, to give an indication of when that channel would have been cut.

Putting these data together over time gives an overall picture of channel switching, often from the same locations ('avulsion nodes'). Sedimentation over the last 200 or so years has been slow but steady with some bank erosion except in areas where river flow has been modified by construction on the floodplain. The occasional temporary reoccupation of channels when floodwaters break through via the avulsion nodes also occurs during more extreme rainfall events.

The Exeter basin

The city of Exeter is situated in a commanding position on a bluff above a bedrock step where the Carboniferous bedrock is unconformably overlain by Permian beds. The floodplain below the city is about 1km wide, and is at the position of the lowest easily fordable point of the river, making the location important since pre-Roman times. Most of the floodplain, however, is now built up and has been heavily modified with weirs, leats and the Exeter Ship Canal, all of which make finding traces of earlier channels difficult.

Mapping of the superficial deposits (British Geological Survey 1995) shows river terraces either side of the basin, the wide floodplain of the Exeter basin on Permian bedrock, and the constriction of the floodplain at Cowley Bridge on Carboniferous material to the north, where the floodplain is shared by the river, a main road and the mainline Penzance to Paddington railway.

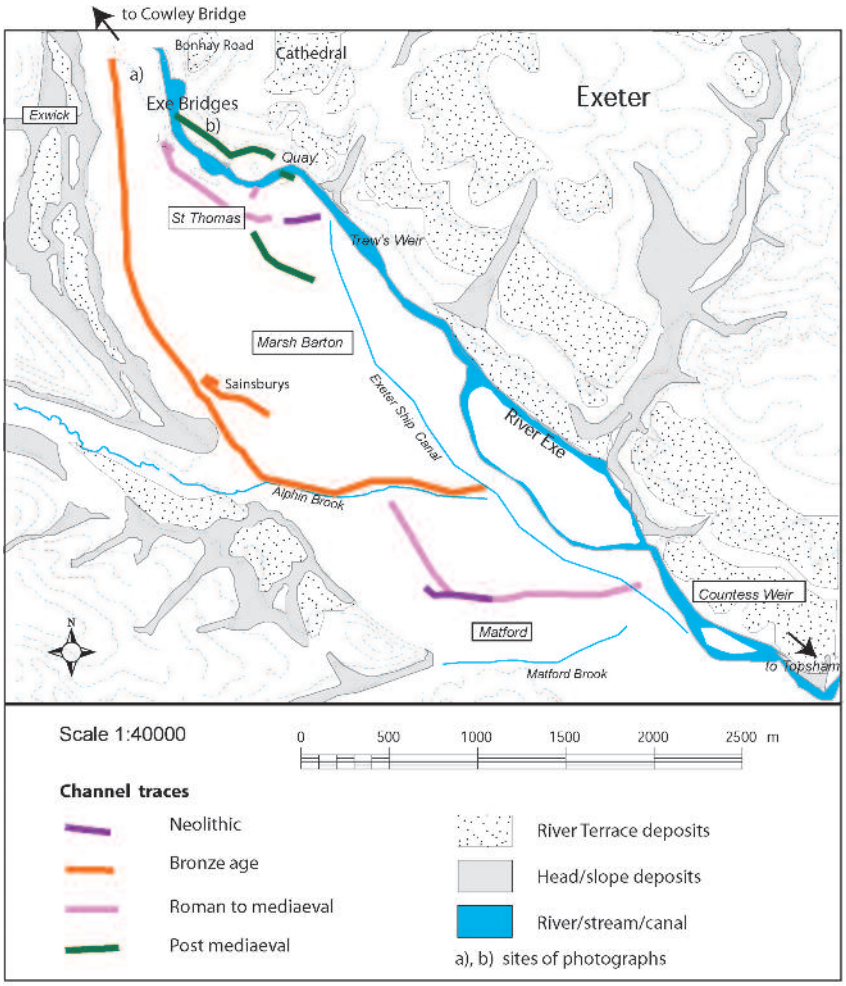
An obvious feature in the basin is the abandoned medieval Exe Bridge (Fig. 5b, *opposite*), which is now to the north of the river; the present bridge is to the right of the photograph. The bridge was built by Nicholas and Walter Gervaise *c.* 1200 and about half of it remains. Records suggest that it was originally between 150m and 180m long and was multi-arched with some arches slightly askew to enable better flow control (Brown 1991). It is thought that the river may have had more than one channel and that the length of the bridge reflects the fact that the whole area was marshy.

There are also several weirs. St James' Weir, for example, has been in place since at least the 16th century, fixing the channel position at that time. Mapping of the sites of mills and mill-related structures in Exeter found evidence for at least eight mills (Watts 2006), and as it is likely that anyone building a mill would use an existing channel if one were available. This evidence adds to the likelihood that the Exe here was multi-channelled. A further feature is the Exeter Ship Canal,which was started in the 16th Century due to a dispute dating from the 12th century when the Countess of Devon put in a weir (The Countess Weir) to force ships to use port of Topsham and so secure her revenues (Clew 1984). This did not please the Exeter merchants and after further weir building occurred to block the river, the Lighter Canal (1539–1697) was built to bypass them, and then deepened and broadened to form the Ship Canal in several stages between 1689 and 1819, finishing in 1830 with a further extension southwards to Turf Lock to completely bypass Topsham. The Ship Canal was a dug channel, but it is likely that it followed lines of drainage for at least some of its course, as it is very sinuous and digging a completely fresh channel would have been much more costly and time consuming.

Archaeological records from the Exeter area

As much of the Exe floodplain is now built up, interpretation of river behaviour is difficult; however, the Exeter Archaeology records, place names (e.g. Marsh Barton, Cuckold's Bridge), remnants of a few channels and bridges and 18th to 20th century maps have all yielded material that has enabled reconstruction of the earlier situation. There is a rich archive of unpublished 'grey' literature from archaeological investigations of development sites across the Exeter basin undertaken by Exeter Archaeology (sadly now no longer operating). Access to these records from the Exeter basin enabled me to collate evidence for any river channels (Bennett *et al.* 2014). The archaeological records include recording of fluvial sediments and records of Carbon-14 dating on organic material. I selected samples from the records of dates from close to channel bases in order to assess the timing of incision, and the data reveal several groups of palaeochannels on the Exe floodplain dating from the Neolithic to at least the 1600s (Fig. 5, *opposite*).

Evidence for river channels has not been found across the entire floodplain, but channels occur on either side of the valley with distinct cross over locations, as at Brampford Speke. There is evidence for channel reoccupation — for example a Neolithic channel in the Matford area is overlain by Roman and medieval material identified by both Carbon-14 dating and pottery. A major



a) View west across Guy's Hylton allotments

b) View southeast across the old Exe Bridge

Figure 5 The Exe Basin, showing the geomorphology and palaeochannel positions deduced from archaeological data with photographs of The Guy's Hylton allotments and the old Exe Bridge.

feature on the floodplain is the distinct channel on the western side that appears to link with present-day streams. This feature can be seen on the ground, particularly in the Guy's Hylton allotments, and in the view to the west towards the valley edge the indentation of the palaeochannel is just visible (Fig. 5a); and the change of slope is clear in spite of the built-up nature of the ground. Mapping during the archaeological excavations revealed a wide channel with an island between two sides of a bifurcated channel (Reed and Sage 1996). Continuation of the long channel appears to go towards the Alphin brook and to the site of a Sainsbury's supermarket in south Exeter at Alphington. When the supermarket site was being developed archaeological investigations revealed further bifurcating silty channel deposits, trending east–west; and directly across the road at the West Exe College later excavations revealed continuation of these channels, which then turn north to join the major north–south channel.

The archaeological evidence gives a picture of a floodplain that had two main channels, and probably vegetated islands in between them. Carbon-14 dates from the archaeological data were put together with OSL dates acquired from channel bases farther upstream, and some clustering of times of incision is indicated. Dates fall in the Late Glacial, with a gap until the Little Ice Age in the 14th–15th centuries, and then a scattering throughout the more recent period. Dates from this study correlate with the clustering of dates shown by research into timing of river incision in Britain (Lewin *et al.* 2005), which groups these by location (e.g. lowland Britain, upland Western Britain).

Historic maps and documents

Exeter has a long history of mapping that has resulted in a sequence of maps from 1587 to the present day. As a group, these maps highlight changes in use of the floodplain, and related modifications of the natural channels. Key features such as the bedrock step and constriction at the northern end of the basin, where the Permian rocks unconformably meet the Carboniferous are clearly shown — an important factor, as this marks the upper limit of navigation. As the early maps do not have consistent orientation for north they can appear inaccurate, but features that were of importance — such as the number of arches in the bridges and positions of leats and channels — are usually carefully drawn. The crossing at the present Exe Bridges appears to be of some age and is on the route of a Roman road, although no sign of any Roman bridge remains; however it is known that the Roman bridges in Gloucester and London were wooden, so the same may apply here and hence preservation is less likely (Hoskins 2003).

Exeter had an important woollen trade and the related use of the floodplain is also reflected in the maps. The 1587 'Hooker' map shows a few tenter racks, where wool fabric was dried after washing; the bedrock step and cliffs at Bonhay Road; and mills and millstreams, as well as what is probably a fish weir at the northern end of the basin. Fish weirs are commonly sited in areas where there is a reasonable flow — here the river leaves a constricted reach and flows into a wider basin. Similarly, to lrun efficient mils there needs to be enough head of water, so

again this position is ideal. The 1765 map also shows tenter racks on the floodplain, more than one channel coming off to a mill, the old Exe Bridge and the island of Great Shilhay (Fig. 6). Over time the channels do appear to have been 'tidied up', particularly in the 1852 map, and are not shown on modern maps, although traces can still be seen on the ground. The maps give a picture through time of a complex reach with islands and multiple channels.

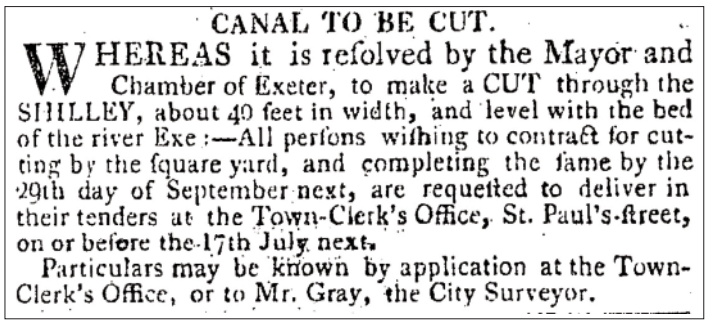
Other printed sources, such as local newspapers, often hold information on the leats, mills and channels — such as advertisements searching for people to cut canals and advertisements selling pieces of land next to the canal in, for example, the *Trewmans Exeter Flying Post* (Fig. 7, *opposite*). Such advertisements can help to pinpoint when further cuts were made across the islands on the floodplain.

Flooding

The low-lying areas of the floodplain have had a history of flooding, and wet ground is reflected in place names such as 'Marsh Barton', 'Water Lane' and 'Marsh Green'; and by the very long 12th/13th century Exe Bridge that probably crossed more than one channel as shown in the maps of 1709 and 1761. Many other human modifications of the river have been made to counteract the serious problems caused by flooding. The most recent of these are the two large spillways constructed between 1965 and 1979 in response to the October and December 1960 floods and which are currently (2016) being further improved. The present-day river is constrained, so if flow increases rapidly then water overtops into the flood relief channels.

A particular problem area is to the north of the Exeter basin at Cowley Bridge, where the tributary River Creedy joins the Exe. There have been major problems with flooding and disruption of the Penzance–Paddington railway line here, as the valley is constricted (underlain by Carboniferous bedrock). There is an engraving from 1855 showing floods at Cowley Bridge. More recently, in 1960, serious floods affected the area. Up to this period, water meadows existed around the St Davids and Exwick areas that did 'soak up' excess water, but in 1960 massive amounts of rainfall caused much damage to the low-lying parts of the city due to peak discharges of up to $700m^3s^{-1}$ (Elsom and Keene 2003), so flood prevention measures were put in place with two major spillways, one to the north of the city, the other running parallel to the Ship Canal. Floods recurred in 2000, 2012, 2014 and in November 2016, when at the time of writing, the Cowley Bridge area of the rail line and road has again been closed. High discharges ($500m^3s^{-1}$) and serious flooding in the autumn and winter of 2000 resulted in closure of the main Penzance to Paddington railway line. Unfortunately, initial repair

Figure 6 Exeter, historic maps: (a) 1587 map of Exeter, Hooker; (b) modern view to Bonhay Road cliffs (J. Bennett); (c) 1765 map of Exeter; (d) 1852 Rapkin map of Exeter (reproduced with kind permission of Devon Archives and Local Studies Service).



CANAL TO BE CUT.

WHEREAS it is resolved by the Mayor and Chamber of Exeter, to make a CUT through the SHILLEY, about 40 feet in width, and level with the bed of the river Exe:—All persons wishing to contract for cutting by the square yard, and completing the same by the 29th day of September next, are requested to deliver in their tenders at the Town-Clerk's Office, St. Paul's-street, on or before the 17th July next.

Particulars may be known by application at the Town-Clerk's Office, or to Mr. Gray, the City Surveyor.

Figure 7 Advert in the Exeter Trewman's Flying Post for canal cutting across the 'Shilley', December 1804.

works did not leave culverts open, so further heavy rainfall ten days later resulted in the river overtopping the embankments and reoccupying an older palaeochannel route towards the railway line, destroying embankments and once again disrupting the rail service. In December 2012, November 2014 and November 2016 the situation re-occurred. Part of the flooding at Cowley Bridge in 2000 was due to culverts not being reinstated, but after heavy rain the volume of water in the river still causes problems. Modelling of where flooding might be expected has been produced (Environment Agency 2016) and work on further flood defences in the area of floodplain most at risk in Exeter started in November 2016, but most of this new work is taking place downstream of Cowley.

Implications and discussion

Demand for building land has resulted in more usage of floodplains, which means that seasonal flooding causes more damage to infrastructure and homes than was the case in the past. In the Exe Valley older settlements are usually situated on higher ground — the main city of Exeter and the village of Brampford Speke are cases in point, lying well above the floodplain. In less populated areas of the valley older buildings are usually a good indication of what is likely to be safe from flooding, and older farmsteads can usually be found above the floodplain up on river terrace deposits. Buildings on the floodplain itself have had problems, including one where the farmer had taken the risk, saying that he had been told that there was a risk of flooding in one year in 50; but unfortunately he was badly affected by flooding in 2012, 2014 and 2016. Indeed, the old Exe Bridge regularly suffered collapses in winter floods, particularly on the western arches where flow was strongest (Brown 1991). A more recent example is the supermarket built in 2009 on the wide floodplain of the River Creedy that had problems with basement flooding within a year of its construction.

How much of this heavy rainfall and flooding has been triggered by climate and how much by human influences has importance for predicting future behaviour, as changes in climate and more intensification of winter storms will affect supply of water and sediment, while alterations to the floodplain will impede flow. The impermeable nature of the bedrock in the Exe catchment means that any rainfall on higher ground will be reflected in the volume of water reaching the downstream sections. The Exe is prone to switching channels and in the past had more than one channel, both of which behaviours could be a natural response to changes. The river has also been constrained and channels modified; however, there is still an imprint of the natural system present that suggests that the major driving force is climatic.

The study of one small catchment can be used to make comparisons with others — John Lewin has written extensively on the topic and notes the effects on floodplains of building railways and railway stations (e.g. Derby, Bristol Templemeads), and the effects of industrial waste and made ground (e.g. Sheffield, Manchester and South Wales). He also discusses the effects of reservoirs, flood-relief channels, embankments and 19th century clean-ups and sewage schemes (Lewin 2013). Changes in the geomorphology of a floodplain will result in different erosion and sedimentation patterns (as shown at both Exeter and Brampford Speke), and anthropogenic modifications may well enhance these patterns, particularly in extreme weather events. Lewin suggests a four-phase floodplain transformation model that covers the last 400 years and also stresses that "understanding the last four centuries of floodplain history can aid enlightened remedies and adaptations".

Conclusions

The timing of channel incision of the Exe appears to correlate with other lowland rivers in the UK, which further suggests that the times of incision are climate controlled.

The implications are that human modification of rivers also has significant effects, but these will be imprinted onto the pre-existing natural behaviour, although future extreme weather events may cause further unexpected effects. Knowledge of the natural channel system is important for construction on the floodplain because the natural system will try to reassert itself. Building on floodplains is a risky business!

References

Bennett, J. A. 2005 'Late Pleistocene and Holocene fluvial geomorphology of the River Exe, Devon, UK'. Unpublished PhD Thesis, University of Exeter

Bennett, J. A., Brown, A. G., Schwenninger, J-L., and Rhodes, E. J. 2011 'Holocene channel changes and geoarchaeology of the River Exe, Devon, UK and the floodplain paradox', *in* Brown, A. G., Basell, L. S., and Butzer, K. W. (eds) *Geoarchaeology, Climate Change and Sustainability*. Geological Society of America Special Paper **476**, 135–52

Bennett, J. A., Brown A. G., Reed, S. J. 2014 'Holocene fluvial geomorphology of the River Exe (UK) from archaeological and historical data and implications for urban form'. *Proc Geol Assoc* **125**, 503–10

British Geological Survey 1995 *Exeter, England and Wales Sheet 325. Solid and Drift Geology 1:50 000*

Brown, A.G., Basell, L. S., Toms, P. S., Bennett, J. A., Hosfield, R. T., and Scrivener, R. C. 2010 'Late Pleistocene evolu-tion of the Exe valley: a chronostratigraphic model of terrace formation and its implications for Palaeolithic archaeology'. *Quaternary Sci Rev* **29**, 897–912

Brown, A .G., Bennett, J. A., and Rhodes, E. J. 2009 'Roman mining on Exmoor: a geomorphological approach at Anstey's Combe, Dulverton'. *Environmental Archaeol* **14**, 50–61

Brown, S. 1991 'Excavations on the medieval Exe Bridge, St Edmund's Church and Frog Street tenements, Exeter, 1975–9'. Unpublished report of the Exeter Museums Archaeological Field Unit Report: **EMAFU Report No. 91.52**

Clew, K. R., 1984 *The Exeter Canal*. Chichester: Phillimore

Edwards, R. A., and Scrivener, R. C. 1999 'Geology of the country *around Exeter'. Memoir of the British Geological Survey Sheet 325 (England and Wales)*

Elsom, D., and Keene, P. 2003 *Exe in Flood*. Oxford: Thematic Trails

Environment Agency 2016 *Exeter_PF_Profile_final.pdf*. **http://www.eacg.org.uk/Docs/PF/Exeter_PF_Profile_final.pdf** (accessed 16/12/16)

Gregory, K. J. 1997 'River Exe at Brampford Speke, Devon', *in* Gregory, K. J. (ed) Fluvial Geomorphology of Great Britain. Geological Conservation Review, Chapman and Hall, 252–5

Hooke, J. M. 1977 'The distribution of changes in river channel patterns: the example of Devon', *in* Gregory, K. J. *River Channel Changes*. Chichester: John Wiley, 265–80

Hoskins, W. G. 2003 *Devon* (rev ed). Chichester: Phillimore

Lewin, J. 2013 'Enlightenment and the GM floodplain'. *Earth Surface Processes and Landforms* **38**, 17–29

Lewin, J., Macklin, M. G., and Johnstone, E. 2005 'Interpreting alluvial archives: sedimentological factors in the British Holocene fluvial record'. *Quaternary Sci Rev* **24**, 1873–89

Reed, S. J., and Sage, S. A. 1996 'Archaeological Evaluation at Guy's Hylton Allotments, Okehampton Road,Exeter'. Un-published report of the Exeter Museums Archaeological Field Unit: **EMAFU Report No. 96.46**

Silvester, R. J., Berridge, P. J., and Uglow, J. 1987 'A fieldwalking exercise on Mesolithic and Neolithic sites at Nether Exe'. *Devon Archaeol Soc Proc* **45**, 1–21

UK National Ecosystem Assessment 2011 *UK National Ecosystem Assessment: Synthesis of the Key Findings*. UNEP-WCMC Cambridge

Watts, M. 2006 *Watermills*. London: Shire Publications

How the weather shapes the West

Felicity Liggins

Meteorological Office
Senior Applied Climate Scientist | STEM Outreach Manager

[Unfortunately, Ms Liggins was unable to write up her lecture as an article for the OUGS Proceedings*. In communications about writing up her lecture, Ms Liggins requested and was provided with a near-verbatim transcription of her lecture recording. However, there were many queries in the text and editing of the transcribed text into a readable article was not accepted. Therefore, according to our OUGS Symposium lectures policy, it is only possible to publish the abstract he submitted to the OUGS 2016 Exeter Symposium Committee for the Symposium brochure.]*

Abstract

More than 118 million people visit the south-west of England each year, either on day trips or for longer, overnight stays. Many of these are attracted by the stunning coastline and picturesque coastal villages, vibrant cities packed with history and culture, and peaceful countryside perfect for outdoor activities. The 'South West' is shaped by its geology, its history and its people and all of these are influenced by our weather. Recent storms have brought widespread flooding and coastal erosion, leading to many millions of pounds-worth of damage and severe disruption to transport links and the economy. Heatwaves can bring tourists flocking to the region, but they can also pose health risks to vulnerable populations and increase stress on our environment and agricultural businesses. [Ms Liggins talked about how the weather of today and in a changing climate, about the weather of the future, and about helping to shape the way we live in the South West and how we might adapt to whatever the future might bring.]

Book review

Siegel, Frederic R. 2016 *Mitigation of Dangers from Natural and Anthropogenic Hazards: Prediction, Prevention, and Preparedness*. Springer.com (ISBN 978-3-31938-874-5; paperback; 127 pages; £37.99, e-book £29.99)

This is a book that I asked for the OUGS to review because I expected someone doing the OU Geohazards course would be interested in doing so. No one was, so after six months, I decided to review it myself. And I am very pleased that I did. This slim volume (only 127 pages approx. A5 size), from Springer Briefs in Environmental Science Series, proved to be a very interesting but ultimately a very sad little book. It has 21 chapters, plus a preface and an epilogue, and is filled with concise detail, with lots of references given at the end of every chapter. It is current, with some references made to disasters in 2015.

It is a summary of all the various types of natural and anthropogenic hazards one could possibly imagine (and occasionally ones I'd never thought about). It explains what they are and how they might happen (or have happened in the case of many anthropogenic occurrences). Siegel then moves on to look at how they may be/have been predicted: or in some instances that they can't be predicted with any accuracy — e.g. earthquakes. What mitigation measures could be taken by the local, regional and often central governments is covered. This includes prevention, preparedness and a chapter I found particularly fascinating (obviously I'm a bit of a nerd) on 'Insurance'.

The book seems to be aimed at non-specialists: one could almost believe it is aimed at governments and land-use planners. It covers a huge range from the obvious geological hazards through climate change, disease and pollution, and ends with conflicts and wars, which Prof. Seigel regards as anthropogenic hazards. While I would say that none of it came as too much of a surprise (I've lived long enough), it brought everything together in one place.

And why do I consider it a sad little book? Because it reflects the damage that we, humankind, have done to the planet and for which, quite frankly, we have neither the money nor, in many areas, the will to put right. Siegel cites many examples of clean ups being attempted. There is a complete chapter on 'Mitigation Economics'. He puts forward many examples of actions that can be taken, including some simple things, such as longer nails on buildings at risk of tornado. He mentions land-use planners frequently: clearly he feels that they shoulder some of the blame, e.g. when considering new developments. Prof. Seigel mentions the environment frequently, pointing out how important it is not just for the biotas there, but also for the societies living near by.

The book is easy to read and can be done in small chunks. It tends to be in American English, but Siegel has tried to reduce jargon. This book is a worthwhile (if rather depressing at times) read and I would suggest that Geohazards students do give it a whirl — you may find something new.

— Jane A. Michael, BSc Hons (Open),
OUGS Archivist/Review Officer

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Book review

Ehlers, Jürgen, Hughes, Philip, and Gibbard, Philip 2016 *The Ice Age*. (Chichester: John Wiley & Sons Ltd (ISBN 978-1-118-50780-3; 548pp; £42.50)

The period we live in at present is the Ice Age and is a period characterised by extreme climatic variations, which continue today. We can only determine what happened in the Ice Age by reconstructing it from traces left in the landscape. This book sets out to describe those landscape changing processes and the methods by which they can be investigated. (This edition builds on an original German language edition by Jürgen Ehlers.)

Ehlers worked as a Quaternary geologist at the Hamburg State Geological Survey, Hughes is Reader in Physical Geography at the University of Manchester and Gibbard is Professor of Quaternary Palaeoenvironments in the Department of Geography, Cambridge University.

An introductory chapter takes us through the development of the understanding of ice ages from Agassiz in 1837 through causes of ice ages and Milankovitch's explanation of orbital cycles. Following this, the story becomes that of the Quaternary, with a large number of chapters taking us through the course of the Ice Age, ice and water processes, and onwards to interglacials and the effects of ice on the landscape. Although the main emphasis is on the Quaternary in Europe, there is a section on North American Quaternary history and, in a chapter on the extent of glaciers, there is coverage of glaciation worldwide. In addition, throughout the book there are references to localities all over the world.

The division of the book into the selected chapters works well and allows selective reading according to the needs of the reader. A slight mystery is the ordering of the chapters; for example, 'Maps: Where Are We?' follows two chapters on post- and periglacial landforms and two chapters before a chapter on the periglacial areas. Following further chapters on various elements of landform effects of deglaciation, the authors give a clear explanation of climate modelling and reconstruction of the Quaternary. A final chapter examines the 'Human Interference' on climate from the leaving of Africa, through the Holocene and up to the Anthropocene.

The book is well illustrated with clear pictures and figures; these and all the tables from the book are available for downloading from the companion website: **http://bcs.wiley.com/go/ehlers/iceage** — a useful source of information, free to use for your own purposes and teaching, and they are easily viewed by browsing chapters or resources. A lengthy and comprehensive reference list provides a huge source of additional material for those who wish to take the subject further.

I can thoroughly recommend this book, which clearly meets the back-cover claim to be ideal for under- and post-graduates studying the Quaternary, and for researchers in climate and environmental change as well as geology.

— Mike Hermolle, BSc Hons Natural Sciences (Open), continuing ES student (MSc in Earth Science)

Book review

Harff, J., Bailey, G., and Luth, F. (eds) 2016 *Geology and Archaeology: Submerged Landscapes of the Continental Shelf*. London: The Geological Society (ISBN 978-1-86239-691-3; hardback, 294pp; £110)

This book appealed to me as I had recently read the award-winning fictional series by Jan Auel describing the life of early hominids in the Ice Age. I hoped to gain insight into the conditions that allowed for the spread of hominids and to see how the geological record aided the research into our early history.

This book is a collection of papers resulting from a Symposium held in Brisbane in 2012, which explored the multi-disciplinary research, using rapidly changing technology, into the potentially rewarding zone of the Continental Shelf. This research explores the influence of changing sea levels on the availability to Anatomically Modern Humans (AMH) of habitable regions that are now submerged and potential routes to new areas of colonisation. There are 13 papers in all, 6 from the Symposium, 6 solicited especially to give an overview of the work in other regions and an introduction written by the editors. The areas covered include Northern Europe (Norway and the eastern Baltic), the Mediterranean, South Africa, S. E. Asia and Australia. It is fully indexed.

The review papers give a good insight into the multidisciplinary nature of the work and describe the way that the geology and archaeology can be linked, each to guide the other. This was true in the papers from the Eastern Gulf of Finland where the mapping and accurate dating of successive occupation sites have given a good indication of the changing environments and fluctuations in sea level into the Holocene. The reverse is also true. In the Mediterranean much work has been done to show where land routes would have been exposed on the shelf between Greece and Turkey during lower sea levels and how access was limited even at lowstands by currents in the restricted deep channels caused by geological faults between Sicily and the Italian mainland. These papers then point to specific areas to prioritise future exploration both above and below the present sea level.

This was a difficult but rewarding read. There was a good variety of information, but some of the black and white illustrations were difficult to decipher. The articles are available on the Geological Society website if you have access through the OU. It has added to my knowledge of the geology of these regions and whetted my appetite for more information on how AMH expanded into the habitable areas under changing environmental conditions.

— Averil Leaver, BSc Hons Geoscience (Open)

Dartmoor glaciation

Dr Stephan Harrison

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[OUGS Exeter Symposium: How the West was Made; original transcription by Dick Millard; edited by Dr Harrison and POUGS Editor David M. Jones.]

Introduction

First I am going to talk about ice limits in the British Isles, then about past views on the glaciation of Dartmoor — I am not the first to have said this; this debate goes back well into the 19th Century, and although some think it is controversial, I do not think it is controversial any longer. Then I will say something about plateau ice fields; I will briefly describe the elements of the glaciation story and finish with some of the other evidence from climate and numerical models, which show why we would expect ice to develop on high ground in the south-west of England].

The first point is that the imprint of glaciers on the landscape can be quite extraordinary. Figure 1 shows a view in western Patagonia almost 2,000m of relief with huge valleys driven by rapidly moving, warm-based outlet glaciers from the North Patagonian ice field. But if you go a few kilometres east, towards Argentina, suddenly the landscape becomes much more subtle. It is still glaciated — you can see a moraine, a roche moutonée and ice-scraped bedrock — but clearly the landscape is much more subtle. This is caused by the very rapid precipitation gradient from the west towards the east of Patagonia.

So I suggest that if you were to look for landscape features such as you might expect in the English Lake District or in western Scotland to demonstrate glaciation on Dartmoor, that is not necessarily going to give the full picture of how glaciers might have driven some of the landscape change.

I would argue that for the last 70 years Dartmoor has been seen as an unglaciated landscape, a landscape where *periglacial* activity has completely dominated (Fig. 2). It is because of this that the 'tor debate', which has been going on since before the 1950s, tells us something interesting about Dartmoor glaciation.

Figure 2 For the last 70 years Dartmoor has been seen as an unglaciated area.

Figure 3 *(overeaf)* shows the ice limits in Britain, reconstructed in a recent study, showing that by the height of the Devensian, the last glacial maximum, ice certainly got down as far as north Devon, and probably down as far as the northern part if the Scilly Isles. During the previous, Anglian, glaciation ice limits reached farther south in the east of England. There have been similar views from various authors, suggesting that we know that ice got to the northern side of the Scilly Isles, but that almost all of the southern and south-western part of the British Isles remained unglaciated — that the south-west moors escaped glaciation.

Figure 1 The imprint of glaciers on the landscape can be either subtle or unsubtle: 1,000m and 2,000m of relief with glacial valleys in Patagonia (left) and in Argentina (right).

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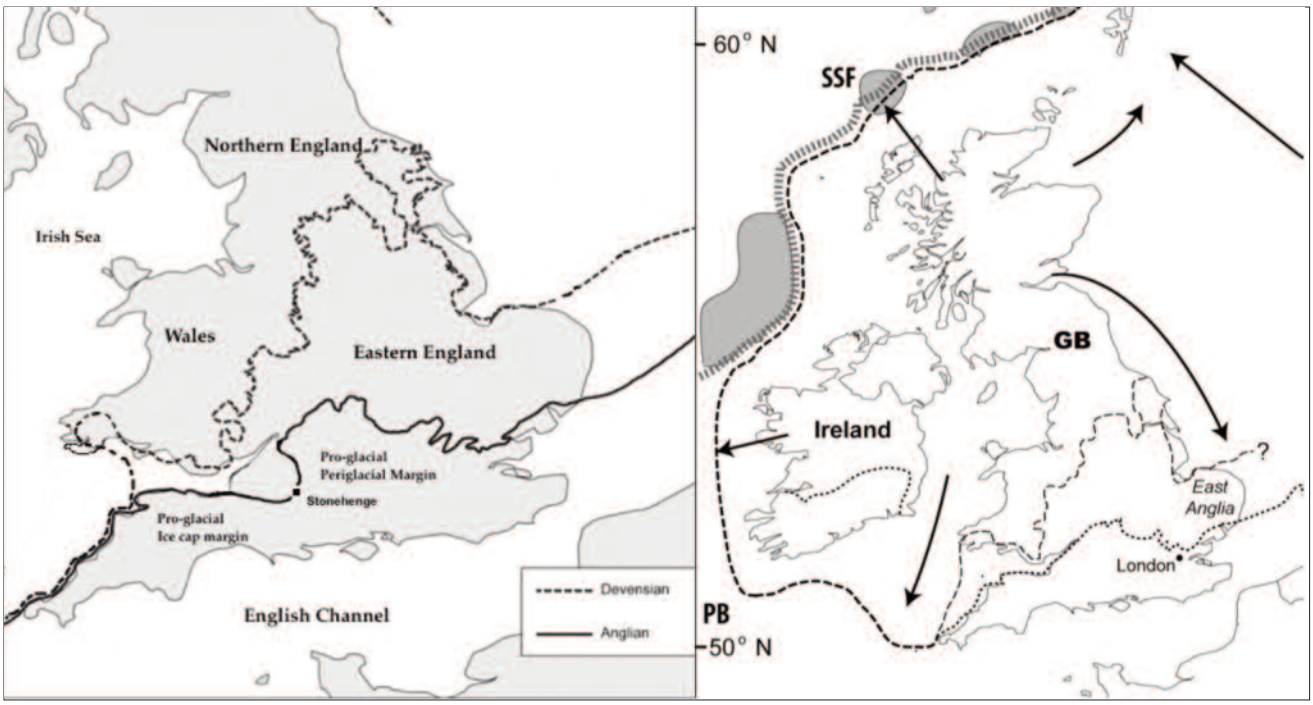


Figure 3 Ice limits of glaciation in Britain.

Early speculation and evidence

We know that the Scilly Isles were glaciated and Figure 4 shows a 1967 map by G. F. Mitchell and A. R Orme demonstrating this. In the northern part of St Martin's and other islands there are small moraines, suggesting that ice sheets moved down from the north and impinged on the northern sides of the Scillies. Figure 5 is of Shipman Head boulder moraine on the northern Scillies, where there is a moraine limit just comprised of boulders. This moraine has been dated, using ^{10}Be, to *c.* 21,000 years ago. This is the Last Glacial Maximum, so we know that the ice sheet reached the northern side of the Scillies at least once, and possibly multiple times during the recent geological past.

Now, there are many reasons why you might get ice sheets going a long way south, but it does suggest that glaciers and ice caps were present on high ground — such as at 500m or 600m in the case of Dartmoor, or 400m in places like Exmoor. You might wonder whether conditions were cold enough to develop plateau ice fields. This has been quite a long debate. J. E. Piller (1917) wrote about evidence of glaciation in the west, and talked about Dartmoor. A. Somervail had already written in 1897 about the absence of small lakes or tarns in the area of Dartmoor; and he argued that Dartmoor had *not* been glaciated because these tarns were absent. Even earlier, in 1869, Ormerod had written that he had not seen any glacial markings on Dartmoor granite, but also stated that the Scandinavian geologist Professor Otto Torrell, "when visiting the moor with him last autumn gave an unqualified opinion that many of the gravels were the remains of moraines" (Ormerod 1869).

Clearly, evidence for moraines in the south-west was being debated in the second half of the 19th century, for J. B. Jukes talked about 'Glaciation in Devon and its borders' as early as 1865!

However, the person who really kickstarted the more recent debate was Ransom Pickard. He was an opthalmist who worked on the western front in WWI and became the Mayor of Exeter, and one of the halls of residence at Exeter University is named after him. He became President of the Devonshire Association and wrote an article entitled 'Glaciation on Dartmoor' in 1943 (Pickard 1943). His paper is qualitative, there are lots of pictures, and the maps are quite poor, and he subdivided the landscape elements that he saw into worn boulders, moraines, grooved rocks, slabs etc. He was the first person to look at this debate systematically — but he was ignored by geologists and geomorphologists. It can be argued that this was because he was not a professional

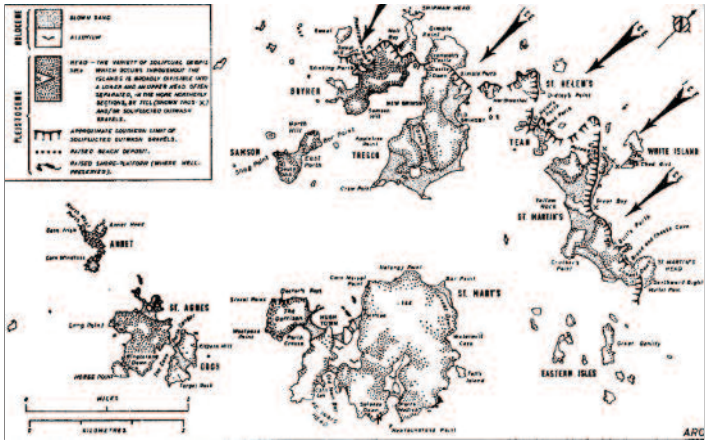


Figure 4 We know Scilly was glaciated.

Figure 5 Shipman Head boulder moraine, Scilly (rucksack for scale) (McCarroll, et al *2010,* Quaternary Science Rev*).*

Figure 6 Small glaciated cirque, Punchbowl, Exmoor.

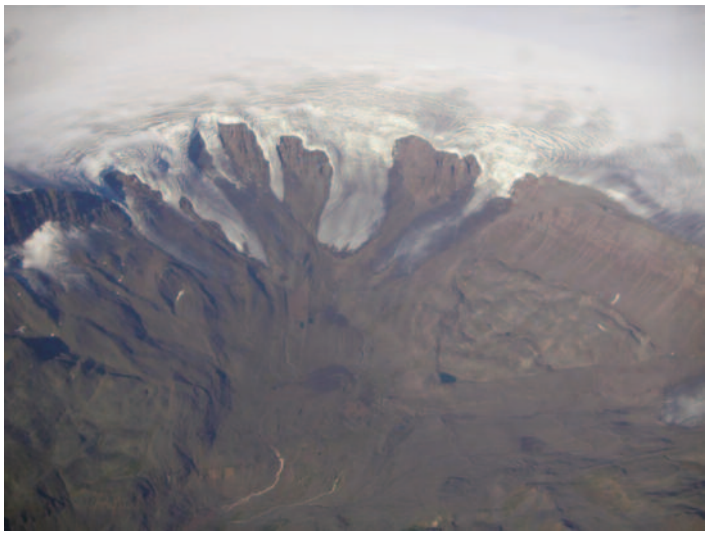


Figure 7 A plateau icefield, Greenland.

geologist, but rather an amateur who did not write anything very technical or empirical, but I think he should be seen as the first person to bring this debate to the fore.

I came across Pickard's work when I wrote a paper in the *Quaternary Newsletter* a few years ago entitled 'Speculations on the glaciation of Dartmoor' (Harrison 2001). I wrote this paper after a walking holiday on Exmoor, on which I had observed deeply incised hollows that looked to me like nivation hollows, or snow accumulation hollows. It does not take much snow for a hollow to get bigger and bigger and for the snow to turn into glacial ice. So maybe there could have been glaciers on Exmoor, but I had doubts, because nobody has ever written about it. So I got out the map looked at where I would expect to find ice on Exmoor. The first thing that struck me was a large hollow called the Punchbowl, which is about 90m deep and several hundred metres wide (Fig. 6). There are ridges in it, and on the basis of that I wrote a couple of papers with colleagues in the late 1990s and early 2000s on the evidence for small glaciers at the Exmoor Punchbowl (Harrison *et al.* 1998, 2001).

Of course, once you start finding ice on Exmoor, the next logical thing is to think, well, Exmoor is pretty high but not as high as Dartmoor, nor as extensive, so there must be evidence of ice on Dartmoor too; and at that point I started looking in the literature, and realised that there was something to be looked at again in terms of the Dartmoor landscape.

The work on Dartmoor

I talked to a colleague and friend of mine at Durham University, Professor Dave Evans, who is a glacial geomorphologist. He has spent a long time working on plateau ice fields in Greenland and in the Arctic. He said that the sorts of landscapes to look for are these plateau ice fields — Dartmoor is relatively flat with large plateau surfaces. Figure 7 shows a modern analogue, from Brice Rea of Aberdeen University. Plateau ice fields develop on very low slope angles with low sub-glacial driving stresses. They are quite thin, and they might well be polythermal and cold based in part, but they do not do much except in small places. They are stationary and essentially protective; it is only when the ice gets thick that they start doing any geomorphological work. So there is limited glacial erosion except when they come off the plateau surfaces, as in these Greenland examples (Fig. 8), in which you can also see moraine limits. Such plateau fields have quite steep valleys, but they are just sitting around; the ice protects the plateau surface, so any glacial evidence is essentially quite subtle except when they start flowing steeply down a valley. Figure 9 shows more examples in Greenland, and also big valley glaciers.

Figure 10 *(overeleaf)* shows blockfields in Greenland. This is a landscape that was underneath ice a few centuries ago, with angular boulders and lots of frost-shattered material. The main point is that these are not classic glacial landscapes with massive U-shaped valleys and huge amounts of erosion as in Figure 1.

Figure 8 More plateau ice fields, Greenland.

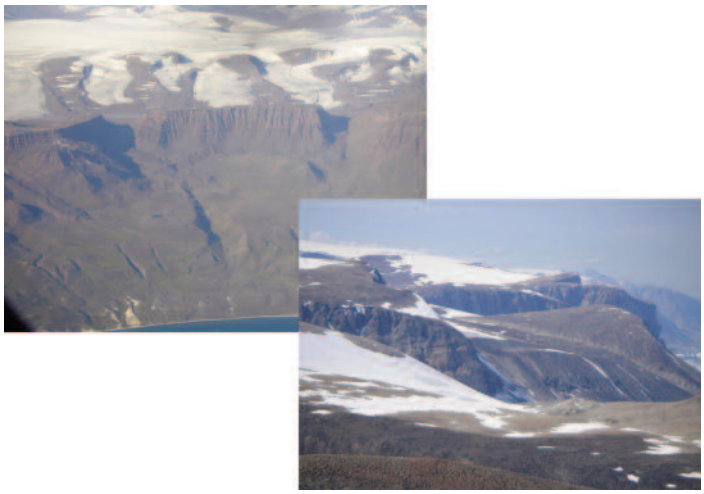


Figure 9 Greenland valley glaciers and plateau ice fields.

Figure 10 Blockfields, Greenland.

With ice plateau surfaces it is only when you get deep valleys that the valleys then become over-deepened. Figure 11 shows landscapes in Arctic Norway and the Lyngen Alps with tors, in an area we know was glaciated just a few hundred years ago. So even tors, which are usually regarded as evidence for no glaciation, can survive glaciation. We know this also from the Scottish Cairngorms, where there are tors with erratics on them at high altitudes.

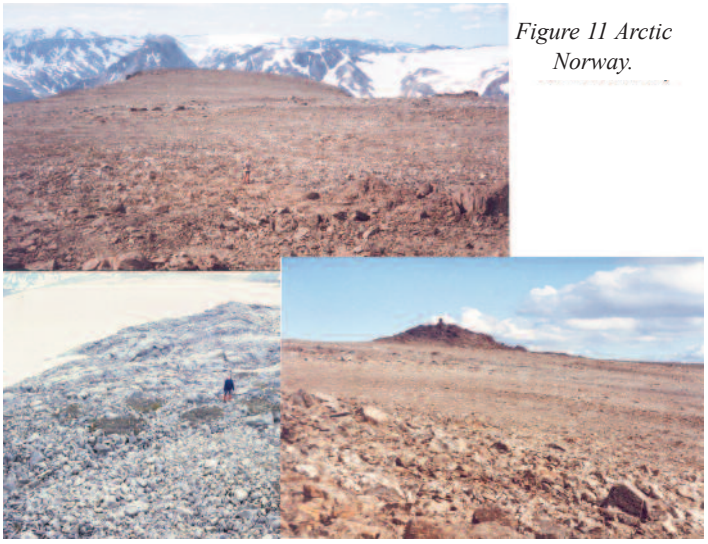


Figure 11 Arctic Norway.

This, then, is the model that we started to think about for Dartmoor. Clearly, we should be looking at the transition between plateau ice fields and the deeper valleys, for it is at the transition zone where we might begin to see some of the evidence.

There are probably at least two phases of ice generation on Dartmoor (Fig. 12). We have looked for evidence mostly in the northern part of the moor, in the West Okement Valley and around Sittaford. We have not yet done any work on the south. Figure 13 is an aerial photograph south of Sittaford Tor. You can see the areas of streamlining, a clear hummocky drift limit, and a series of boulder ridges, which represent drift limits in

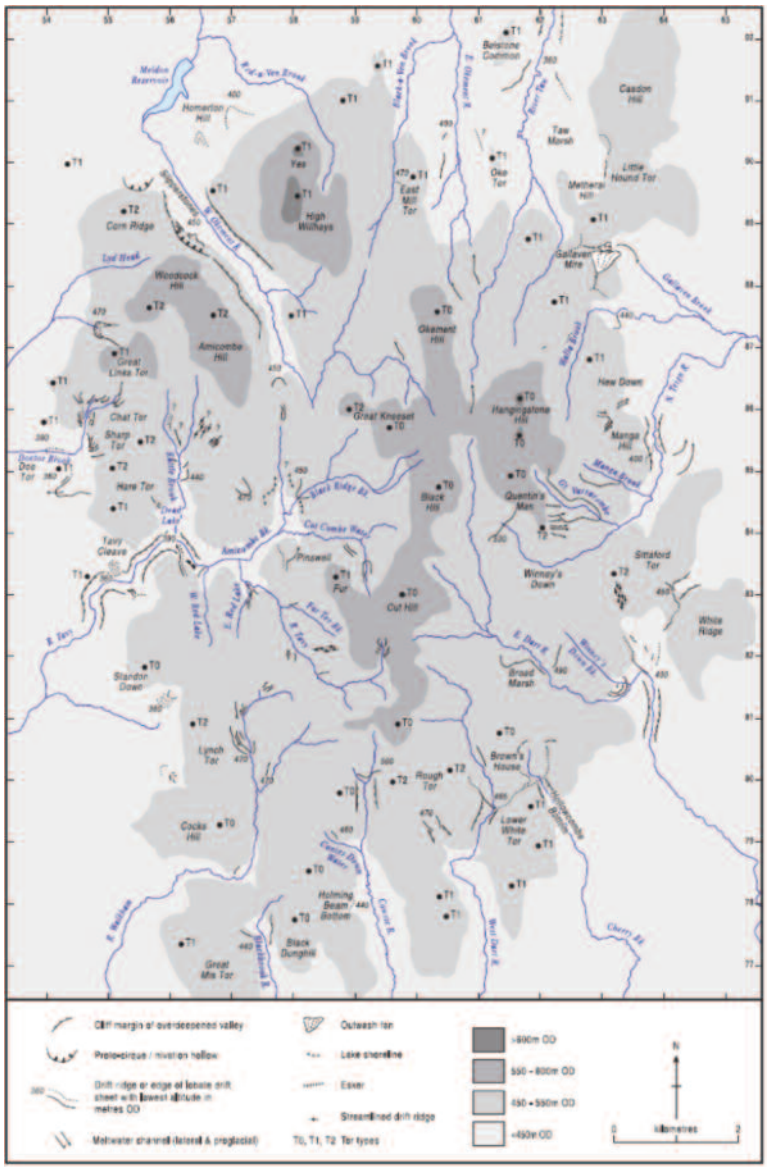


Figure 12 Geomorphology map for north Dartmoor, showing main types of proposed glacial landforms, distribution of tor types and summary contour intervals.

Figure 13 Aerial view of the area to the south of Sittaford Tor, Dartmoor.

Figure 14 Terminal moraine south of Sittaford Tor, Dartmoor.

this area south of the tor. There is a huge ridge that cuts right across the valley.

I put forward a hypothesis: the landscape of Dartmoor is periglacial, so its features must be the results of processes such as frost shattering, solifluction etc. You can test, and challenge, this hypothesis if you can find features that cannot be produced by solifluction or frost shattering.

Considering the constructional ridge right across the valley, if you go up valley, beyond the ridge, you would have to walk up the face of the ridge and right over the top. Figure 14 shows a photograph of the ridge, taken from the left-hand side; so if you walk down the valley, you walk up the ridge to the top and then down again. This ridge goes right across the valley side: it is constructional, made of drift, and it has a boulder on top of it of *c.* 3–4m in size. If solifluction — a periglacial process — created this ridge, that boulder must have flowed up hill! When you stand on the boulder, the ground above you goes away from you. In other words, if the ground came from this hillside, it would have had to flow downhill at 70mm a year and then flow uphill at 70mm a year. Of course, the laws of physics do not allow that.

So we have a constructional feature with, elsewhere, a series of other boulders and ridges, and with isolated boulders stuck right in the middles of these ridges. If you were elsewhere in the

Figure 17 Small lateral moraine fragments, southeast flank of Winney's Down, Dartmoor. with isolated rounded boulders on it.

Figures 15 and 16 (above and below) Two views of Sittaford moraine ridge, Dartmoor.

British Isles you would probably think this landscape looks glacial with a moraine, and a boulder that has been dumped on top of this ridge. However, on Dartmoor, you wonder what else it could be. Figures 15 and 16 are further views, showing Sittaford Tor. This is a massive ridge, well over 100m wide, a big, constructional feature sticking out into the mouth of the valley.

Figure 17 shows another constructional ridge, on the other side of the valley, with isolated rounded boulders on it; and Figure 18 of another ridge, with Sittaford Tor at the top of the picture —

Figure 18 Hummocky moraine south of Sittaford Tor, Dartmoor.

Figure 19 Plateau margin recessional moraine, Tavy Hole, Dartmoor.

another constructional feature, right in the middle of the valley. We have to explain how ridges like these have been made; and the explanation is easy if there was a glacier there, but much harder if driven only by periglacial action. You cannot get constructional ridges like these in a periglacial landscape. I would interpret that as hummocky moraines.

At Tavy Hole on Dartmoor there are quite big lateral ridges (Fig. 19). Look again at Figure 11 (Arctic Norway), at the plateau ice fields. On top there is little happening, just small lateral features, generated as the valley gradient increases, associated with ice tongues coming off the surface of the plateau. And leaving large boulders.

There are lots of boulders on Dartmoor, but what tends to happen where there is a high tor, is that the tor breaks up by some gelifraction or frost shattering process. Material is then sludged downhill by periglacial action and dumped. But it is difficult to explain such large, boulders where upslope of them there are no tors (Fig 20, *left*). Not only that, but, in this example, the boulder is very rounded and just a few hundred metres from the big ridge in Figure 19 of Sittaford. Figure 20 *(right)* shows another boulder, right in the middle of a valley with no tors around it, in the middle of the Sittaford Valley.

These features are easy to explain if the Sittaford Valley had been glaciated; but much harder to explain if has not been glaciated.

Figure 20 Erratics south of Sittaford Tor, Dartmoor.

Figure 21 (above and below) Meltwater channels on Great Varracombe, Dartmoor.

Another feature observed on Dartmoor is what appear to be meltwater channels. Figure 21 *(previous page)* shows an example at Great Varracombe. There are gulleys cut into bedrock, and a whole series of ridges associated with them, even better visible in the aerial photograph. We can explain such constructional ridges in the middle of a valley most easily if there had been ice in them, because these are typical glaciofluvial features associated with water coming from an ice cap or from a valley glacier, including moraines and hummocks (Fig. 22). Such features are much harder to explain with the periglacial hypothesis.

There are even bigger meltwater channels at Hollowcombe Bottom — Figure 23 shows three views of a dry valley, now with small streams; also at Great Varracombe and in the Sittaford Valley, where there is a valley cut into bedrock but with no headwaters or catchment. Now, we know that rivers create valleys, but rivers need headwaters. This is quite a steep valley side (a wall goes into the hollow and comes out of it again) and it has no catchment area; it is simply a linear valley cut into bedrock. You can explain such a feature easily if created by ice in it , because it could be a subglacial meltwater channel. And I would argue that it is much more difficult to explain

Figure 23 Meltwater channels on Dartmoor: (above) at Hollowcombe Bottom, (below) at Great Varracombe and (bottom) at Sittaford Tor.

Figure 22 (above and below) Moraine, glaciofluvial hummocks on Great Varracombe, Dartmoor?

it by purely fluvial processes. This Sittaford example is also running *along* the valley side, whereas if it were a normal fluvial river it would be running downhill.

Another piece of evidence for glacial processes is diamict, of which there is an abundance on Dartmoor as well as the 'normal' sediment on Dartmoor. Normally, periglacial processes produce lots of angular, frost-shattered debris in a weak matrix — so weak that you can put your hand in and pull it out, because there is no over-burden pressure. You just have periglacial activity operating on the first few metres or so of material. However, as shown in Figure 24 Section 3 and Figure 25 at Sittaford Tor, at the top of the section there is hard diamict. It has what looks like a compression fabric down-valley, and it is hard to dig out. I had to use my axe to get it out, and it is only a few tens of centimetres below the surface. In other words, it has been compacted — I would argue by a glacier.

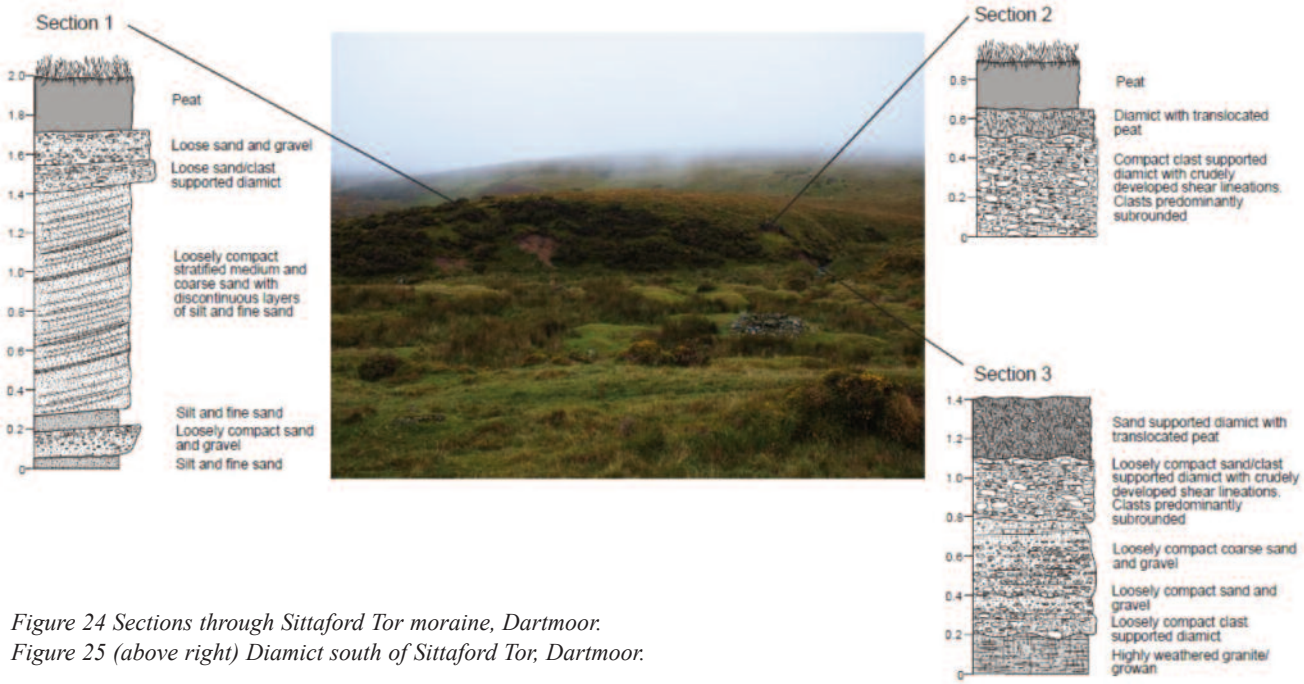

Section 1
Peat
Loose sand and gravel
Loose sand/clast supported diamict
Loosely compact stratified medium and coarse sand with discontinuous layers of silt and fine sand
Silt and fine sand
Loosely compact sand and gravel
Silt and fine sand
Section 2
Peat
Diamict with translocated peat
Compact clast supported diamict with crudely developed shear lineations. Clasts predominantly subrounded
Section 3
Sand supported diamict with translocated peat
Loosely compact sand/clast supported diamict with crudely developed shear lineations. Clasts predominantly subrounded
Loosely compact coarse sand and gravel
Loosely compact sand and gravel
Loosely compact clast supported diamict
Highly weathered granite/ growan

Figure 24 Sections through Sittaford Tor moraine, Dartmoor.
Figure 25 (above right) Diamict south of Sittaford Tor, Dartmoor.

Figure 26 shows similar material in the West Okement Valley. The periglacial material is near the surface, and darker, and underneath it is much more compacted diamict with a strong fabric. It is completely different from the material above it and very hard to get out, and yet it is only half a metre or so from the top of the section. I would argue that this is a classic glacial till.

Another example, on the northern side of West Okement. is at Corn Ridge Hollow (Fig. 27, *opposite*). Here we have what looks like small glacial cirques, shown in an aerial photograph of Corn Ridge (Fig. 28, *opposite*), showing the West Okement River, and, on the Slipper Stones, what we have interpreted as moraine ridges. This demonstrates a phase of restricted glaciation.

At Corn Ridge Hollow (Fig. 29, *opposite*; also in section in Fig. 27), there is a broad hollow with sheep in the distant slope for scale, there is 40m or so of back wall, and some constructional features that might well be ice-marginal features; and the diamict is exposed by the stream channel. The most viable explanation of this diamict is that there was ice compaction of the sediment in here at some stage.

Figure 26 Diamict in West Okemont Valley, Dartmoor.

Figure 27 Diamict with down-valley fabric, Corn Ridge, Dartmoor.

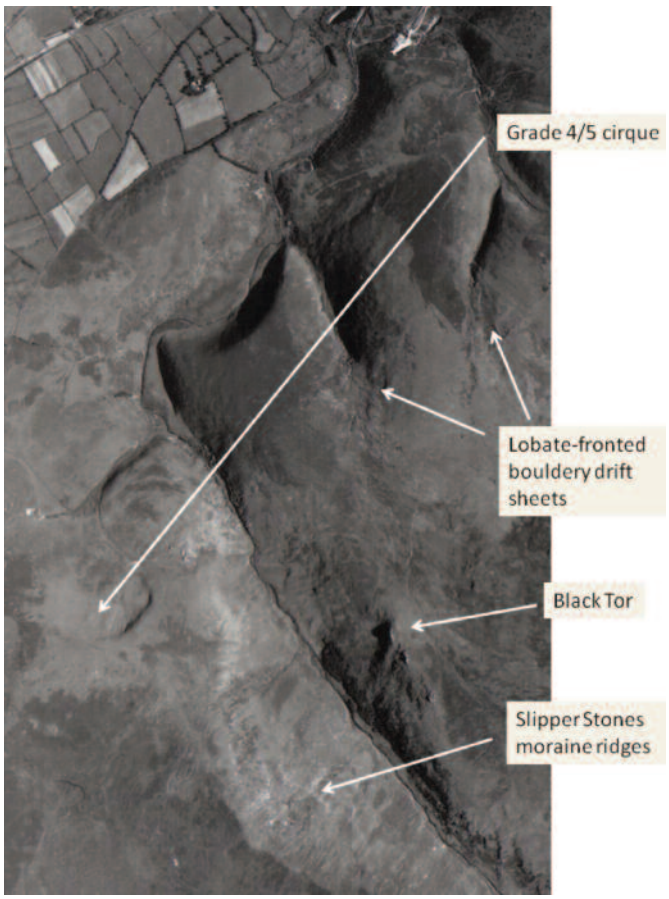


Figure 28 Aerial view of Corn Ridge and Slipper Stones features west of Okemont Valley, Dartmoor.

Figure 30 shows aerial and oblique views of the Slipper Stones and the West Okement Valley, with a quite marked set of cliffs on the western side, and showing a prominent ridge running along it. The aerial view of the ridge shows that it has a series of ridges inside it. Such features are sometimes called a pro-nival rampart: the argument being that sometimes a big patch of snow is up against the cliff, from which boulders fall, roll to the front of the snow patch and form a ridge. There has been much work done on how to differentiate snow patch hollows from glacial hollows. However, here at the Slipper Stones this cannot be the explanation, because that ridge is too far away from the wall. If there had been a snow patch there, it would have been so large that it would

Figure 29 The broad hollow at Corn Ridge Hollow, Dartmoor, showing the back wall and constructional features.

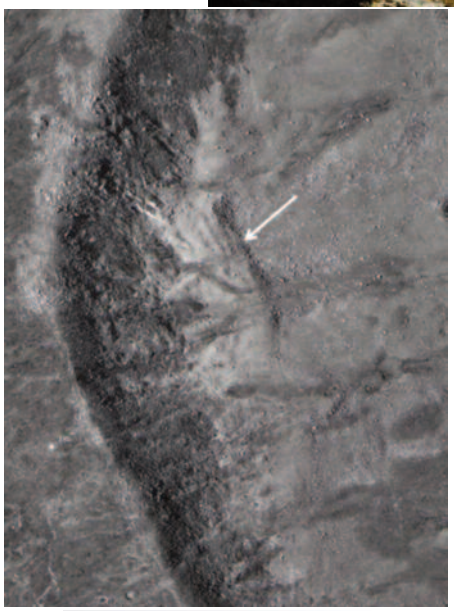


Figure 30 Aerial and two oblique views of the Slipper Stones ridges and West Oakmont valley, Dartmoor.

Figure 31 Ground view of the Slipper Stones constructional ridge, Dartmoor.

Figure 32 View up slope of the Slipper Stones, backwall, showing exposed patches of glacially scoured bedrock (scale of photograph c. *20m long).*

Figure 33 Another exposure of eroded, smoothed bedrock at the back of Slipper Stones, Dartmoor.

turn into glacial ice at the base, and start flowing. This ridge is too far away from the back wall to have been created by snow patches: it has to be created by ice. The aerial view in Figure 30 also shows what looks like a small moraine, but which could have been a small ice cap from a small plateau ice field, producing a load of ice coming down off the hillside. If so, it would be the place to look for glacially abraded bedrock because that is where the ice is flowing fastest.

When we examined the area we found these little ridges inside the main ridge (Fig. 31, with my rucksack for scale), which cannot be explained by periglacial action. It has to be some sort of push feature. A closer view up slope (Fig. 32) shows how steep it is, and that there are exposed patches of glacially abraded bedrock. The argument is that these are plateau surfaces; the ice came over the valley side, travelled rapidly, and produced these concavities, in places even eroding the bedrock. Figure 33 shows another such exposure of eroded bedrock looking very steeply uphill on that same slope. Such eroded bedrock is not found anywhere else on Dartmoor as far as I know, but further exploration might well find more examples.

Clearly, such eroded, smoothed bedrock is not purely periglacial; but it is something you would expect if the area had been glaciated.

Further evidence of glaciation on Dartmoor is incised drift sheets on Sittaford Tor. In Figure 34 there are no tors on this landscape at the top, but yet below, there are erratics. How did such huge boulders — this example is *c*. 2m high and *c*. 5–6m long — get there without a massive tor upslope? There is no tor there, but this is in the middle of the Sittaford Valley where we think an ice lobe came down.

With these examples of evidence for ice plateau glaciation on Dartmoor how can we further test this hypothesis You might argue that the variation in tor size and shape is another clue. We would expect that the high ground would have had ice, and thus that these places would have either very small tors or no tors at all; and, conversely, that the areas where we think there was no ice are where the big tors are found. We could then use the distribution of tors as a test of our hypothesis.

Figure 34 Incised drift and erratic boulder on Sittaford Tor, Dartmoor.

Figure 35 Vixen Tor (Type 1, left), Dartmoor.
Figure 36 Corn Ridge tor feature (Type 2, right), Dartmoor.

So we looked at some of the tors. The Vixen Tor, for example, which we call 'Type 1', is on low ground. It has a high structure, almost castellated, with many boulders lying around, and it is unlikely that it would have survived much glaciation by warm-based ice (Fig. 35). But when you get to the high plateau surfaces, you get much less prominent tor features, heavily eroded, such as this example, which we call 'Type 2, on Corn Ridge (Fig. 36). It is just above the area of smooth, glacially scoured bedrock shown in Figures 32 and 33. Very different from Vixen Tor, it is on the high ground and in an area our hypothesis associated with a plateau ice field. The hypothesis is that either any tors on high ground were eroded by ice, or never developed properly — their development was perhaps impeded.

When a map of tor distribution and types is considered, the absence of tors, or only of poorly developed tors, on high ground mostly correlates to areas where we think the ice developed. Thus tor distribution is a good test of our hypothesis, and supports our hypothesis that ice mainly developed on the high ground.

We can also run a numerical, mathematical model, an ice sheet model, that has no 'knowledge' of glaciation. The results show that when temperature is reduced down to Last Glacial Maximum (LGM) levels, and the precipitation is changed, any high ground (if high enough) will generally develop ice. You can then model where the ice should be — where it would preferentially form. We ran the climate model and the results show that after 665 years it produces the ice surface topography shown in Figure 37a; and after 1,400 years, it generates an ice cap (Fig. 37b). It is a good test, because the model is tested against ice limits elsewhere in the British Isles and it reflects these well. If you run this model for the whole of the LGM, for the entire British Isles, it produces ice limits where we know ice existed. It also produces ice on Dartmoor.

If you then run a model that produces ice flow velocity, then it does what we would expect plateau ice fields to do. On the flat ground, you get low velocities, so there is not much erosion or glacial geomorphology (Fig. 38, *overleaf*). But where the valleys get a bit deeper, ice velocities increase considerably. So the valleys coming off high ground into all these valleys is where ice is increasing velocity. As we know, as ice comes into these valleys, the driving stress increases and so the velocity increases as well, and that is when the ice movement starts to do geomorphological work.

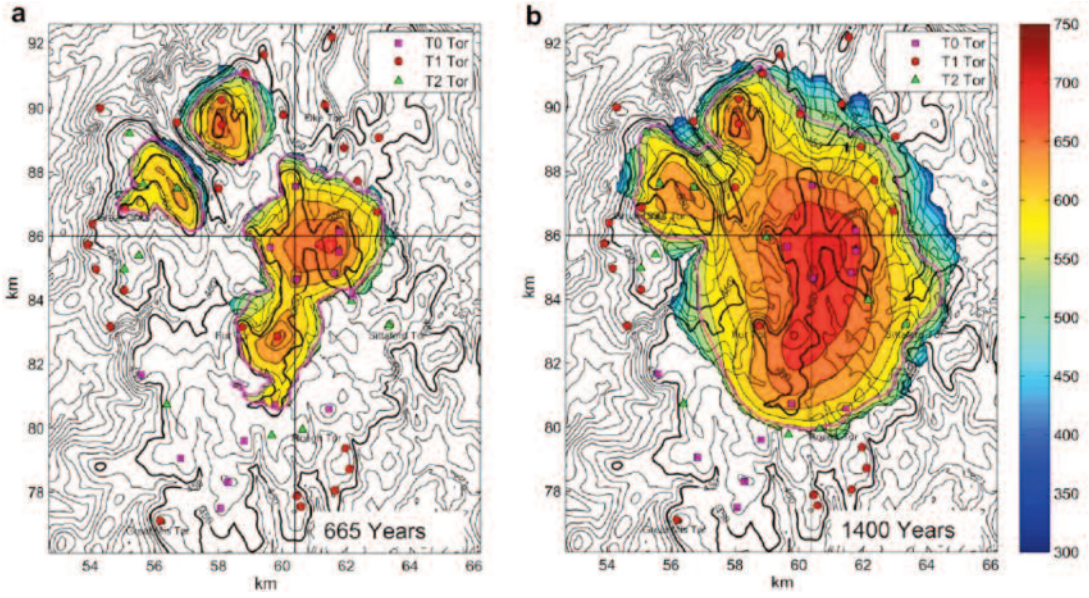
Finally, if we model ice thickness, and run the model for 1,400 years (an arbitrary figure, as the ice may have lasted longer than this or shorter), then we find in certain parts of northern and north-western Dartmoor between 150m and 180m of ice thickness (Fig. 39, *overleaf*).

Modelling

So, we have evidence of ice as far south as the Scilly Isles, and thus hypothesised that ice also formed high up on Dartmoor. We have found landform evidence on Dartmoor, and we have tested that landform evidence against tor development and their distribution. And we have also tested the evidence using a numerical climate model, and it fits.

There are also other climate models, such as those by Alun Hubbard of Aberystwyth University. In 2009 he modelled the British Irish Ice Sheet, based on large ice sheets rather than relatively small features (Hubbard, A. *et al.* 2009). Figures 40 and 41 *(page 85)* show the results of a series of model runs where there was relatively high precipitation over Ireland. The results

Figure 37 Modelling: Time slices of modelled ice surfaces (coloured contours with 25m intervals) for a regional ELA of 550m after (a) 665 years and (b) 1,400 years model build-up times. Basal topography is shown as black contours (thick lines for 450m, 550m and 500m contours) and pink line for ELA position. Locations and classification of tors as coloured symbols (see legend).



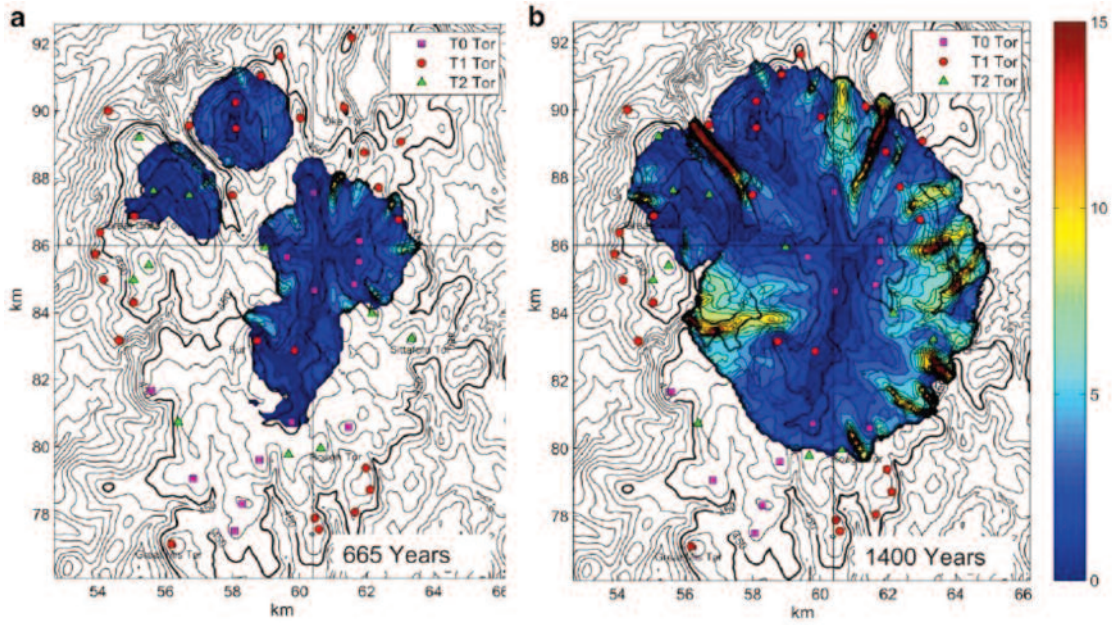


Figure 38 Time slices of modelled ice flow speed in m/y (coloured contours with 1m/y intervals) for (a) 665 years and (b) 1,400 years model build-up times.

show ice covering the whole of south-west England, including cold based ice on Dartmoor, on Exmoor and farther west (Fig. 41). Further, even with low precipitation west of Ireland, you still get ice on Dartmoor.

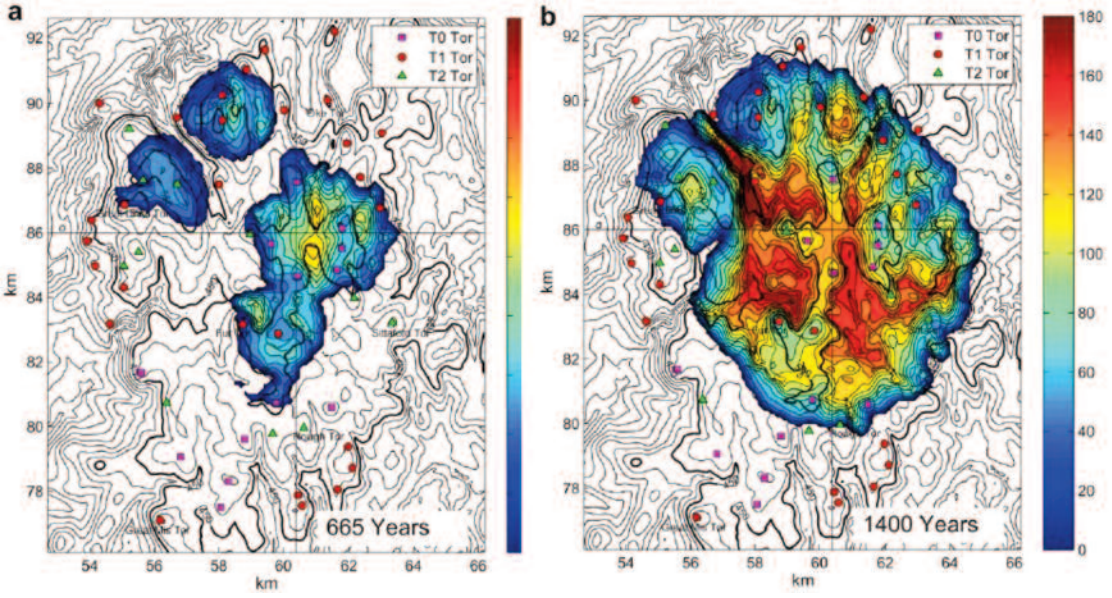
So there are several strands of evidence for ice in southwest England; physical evidence, modelling, tor distribution and landforms all support a hypothesis that Dartmoor was glaciated. It is not surprising that the areas of high ground just outside the main ice sheet should have nurtured their own small glaciers.

Hubbard *et al.*, writing before our most recent work, wrote, "it is difficult to achieve a single 'surge-advance' south to the Scilly Isles without a broad piedmont-type lobe impinging onshore across much of SW England"; and further, that, "The experiments presented also indicate significant excursions of wet-based ice into areas of southern England, where little evidence of recent glaciation has been found".

Finally, Figure 42 is of the Giant's Rock, at sea level at Porthleven, a large boulder never moved by big waves in winter. It is an erratic, but we do not really know where it came from. It may have come from Greenland, or perhaps even Norway. The question is, how did it get there? Some say that it could have rafted on floating sea ice during the Last Glacial Maximum. However, at the LGM sea levels were 125m lower than they are now; you could probably have walked to the Scilly Isles. So the question remains: how did the Giant's Rock get to the shore at Porthleven?

There are many conundrums in the glacial story of south-west England. Figure 43 shows the climate record for the last 28,000 years. So, when would I argue that glaciation occurred in Dartmoor? I would argue that in that small cirque on the northern side of West Okement Valley where we had areas of ice-scoured bedrock, may well be of Younger Dryas age, perhaps 10,000 to

Figure 39 Time slices of modelled ice thicknesses in m (coloured contours with 10m intervals) at (a) 665 years and (b) 1,400 years model build-up times.



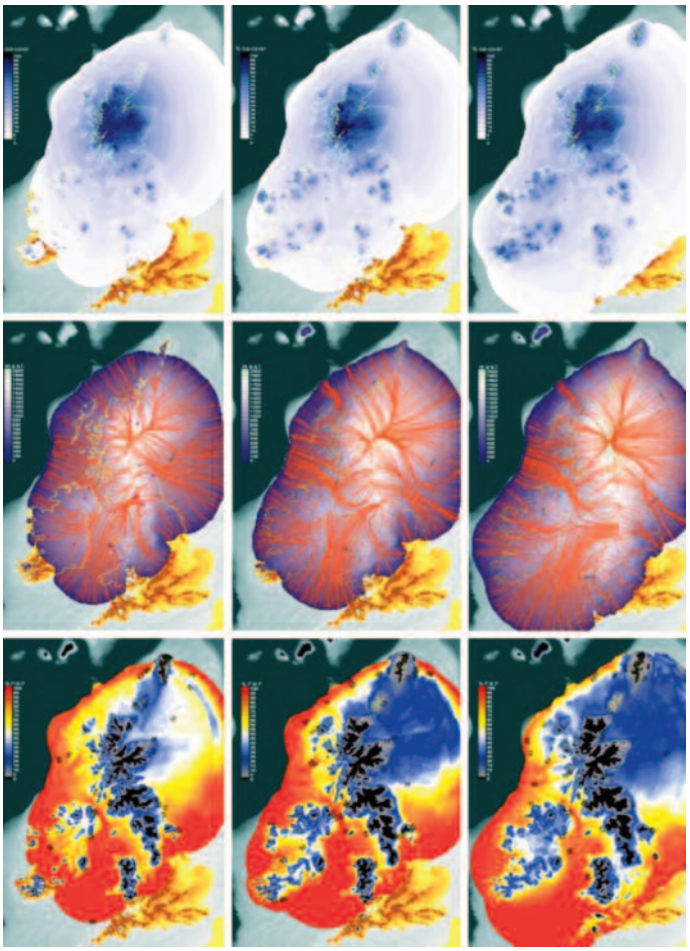


Figure 41 Model outputs from E109b3: high precipitation over Ireland.

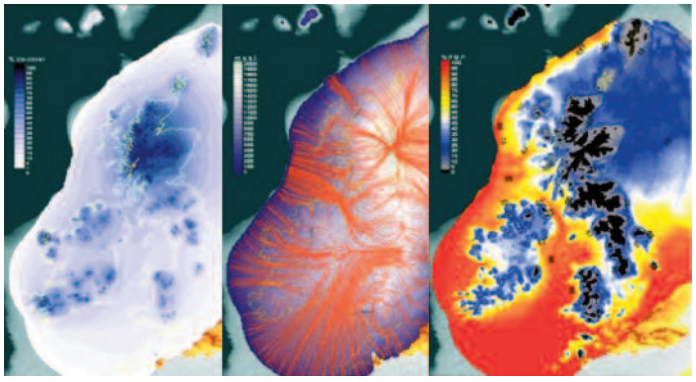


Figure 43 NGRIP ice core age records (Harrison et al. *2010).*

12,000 thousand years ago. But I would argue that the main glaciation in south-west England was during the LGM, with a renewed phase some time later. But this is pure speculation, for no dating has been done.

Summary

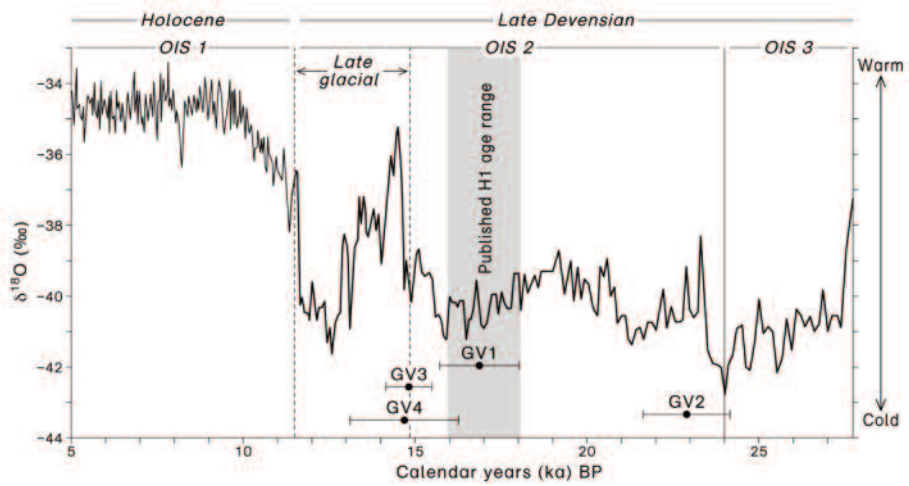
I would argue that:

• Dartmoor is the southernmost glaciated landscape in the British Isles: I can provide copies of our 2012 *Quaternary Science Reviews* paper to anyone who is interested.
• There is geomorphological and sedimentological evidence for this glaciation. This is supported by theoretical evidence and modelling considerations.
• This evidence overturns the long-held view that Dartmoor escaped glaciation, and adds a new twist to the age-old tor debate. Ransom Pickard was completely ignored for decades, and it is nice to show that, even though he was an amateur, he was right.

[References, overleaf.]

Figure 40 (left) Modelling the BIIS: top, cumulative ice cover as a percentage of the total simulation time (Maximum ice sheet limits are white); middle, modelled ice-sheet surface geometry and associated flowlines for the time-slice corresponding to maximum areal extent; bottom, cumulative time that the ice sheet bed was at PMP expressed as a percentage of the total simulation time (black shading = persistent frozen basal conditions, as %PMP < 2.5%). These figures correspond to experiments (i) E102b2m (ii) E109b8 and (iii) E109b3 (Hubbard et al. *2009).*

Figure 42 Giant's Rock, Portleven.



References

Harrison, S. 2001 'Speculations on the glaciation of Dartmoor'. *Quaternary Newsletter* **93**, 15–26

Harrison, S., Anderson, E., and Passmore, D. G. 1998 'A small glacial cirque basin on Exmoor, Somerset'. *Proc Geol Assoc* **109**, 149–58

Harrison, S., Anderson, E., and Passmore, D. G. 2001 'Further glacial tills on Exmoor, southwest England: further implications for small ice cap and valley glaciation'. *Proc Geol Assoc* **112**, 1–5

Harrison S., Glasser N. F., Anderson, E., Ivy-Ochs, S., and Kubik, P. 2010 'Late Pleistocene mountain glacier response to North Atlantic climate change in South West Ireland'. *Quaternary Science Rev* **29**, 3948–55

Evans, D. J. A., Harrison, S., Vieli, A., and Anderson, E. 2012 'The glaciation of Dartmoor: the southernmost independent Pleistocene icecap in the British Isles'. *Quaternary Science Rev* **45**, 31–53

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., and Stoker, M. 2009 'Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British-Irish ice sheet'. *Quaternary Science Rev* **28**, 759–77

Jukes, J. B. 1865 'Glaciation in Devon and its borders'. *Geol Mag* **2**, 473

McCarroll, D., Stone, J. O., Ballantyne, C. K., Scourse, J. D., Fifield, K., Evans, D. J. A., and Hiemstra, J. F. 2010 'Exposure-age constraints on the extent, timing and rate of retreat of the last Irish Sea ice stream'. *Quaternary Science Rev* **29**, 1844–52

Mitchell, G. F., and Orme, A. R. 1967 'The Pleistocene deposits of the Isles of Scilly'. *Quart J Geol Soc London* **123**, 59–92

Ormerod, E. 1869 'Sketch of the granite of the northerly and easterly sides of Dartmoor'. *Report of the British Association, Transactions of the Sections*, 98–9

Pickard, R. 1943 'Glaciation on Dartmoor'. *Trans Devonshire Assoc* **75**, 25–52

Pillar, J. E. 1917 'Evidence of glaciation in the west'. *Trans Plymouth Inst* **16**, 179–87

Somervail, A. 1897 'On the absence of small lakes or tarns from the area of Dartmoor'. *Trans Devonshire Assoc* **29**, 333–9

Exeter Symposium 2016: How the West was Made
Summing up

Dr Steve Blake, OUGS President

(Senior Lecturer in Earth Sciences, The Open University)

First of all, I want to thank Sheila Alderman (Branch Organiser, OUGS Wessex Branch) and all her team for putting on such an entertaining and informative Symposium. That twice as many people attended as had initially been expected is a great credit to their advertising campaign, and to the strength of the programme of speakers, field trips and social events. Thank you all very much!

To sum up 11 wonderful presentations is quite a task. Every presenter shared their passion for their subject brilliantly and brought us bang up to date with current thinking on their topics. They showed that the Southwest is a great place to see and do geology. But rather than summarise each talk I want to identify some themes and connections that came to mind as I listened to the talks and the discussions that followed.

On Friday evening, Iain Stewart gave us a fascinating talk on how scientists, and geologists in particular, face a number of challenges that we might not think of when we're trying to give science-based advice to someone who isn't as excited by science as we are. Scientists need to gain the skills for doing science of course, but they also need to learn skills for effectively communicating their knowledge to people who don't have that knowledge and may very well be resistant to gaining it. That's why university science degree courses, including those at the OU I'm glad to say, make a point of teaching how to transfer scientific information to non-experts by avoiding jargon and explaining things as simply as possible. However, Iain showed evidence that it isn't people's lack of knowledge that is necessarily the problem. In some cases, people can be resistant to changing their instinctive beliefs, and they express outrage when those beliefs are challenged, so no end of explaining the facts to them will alter their outlook. There can be more to bringing science-based evidence to the public than we sometimes assume.

Iain also pointed out that geologists are not 'normal' people. He described how most members of the general public tend not to think in three dimensions as instinctively as Earth scientists do. We geologists take thinking in 3D for granted, and are equally at home looking at a cross-section as a map, but he has found that the general public often have little appreciation of what really lies beneath their feet. That revelation got me thinking that geologists also have a well-developed ability to think in the fourth dimension of time, especially in terms of great swaths of geological time. That must make another challenge when we try to tell non-geologists about the geological record of environmental change that is now an important aspect of the whole debate around environmental change.

The four-dimensional aspects of geologists' thinking came into play first thing on Saturday morning when Robin Shail, Richard Scrivener and Sarita McVicar-Wright covered the regional geology of the Southwest, from 500 million-year-old Lizard basement rocks through to Permo-Triassic sedimentary environments.

In two back-to-back presentations Robin showed off the power of 4D thinking. He presented the evidence for an ancient suture zone lurking off the south coast — the site where the Rheic Ocean first opened and then closed. Plate tectonics controlled non-marine and marine sedimentation, presence of faunal provinces, incorporation of slivers of crystalline and mantle basement rocks, alternating periods of compression and extension on faults to create the tectonically-controlled sedimentary and environmental history held in the rocks, and the spectacular structural and igneous geology of the Southwest. Robin was careful about describing the evidence and acknowledging that uncertainty in geological evidence leads to uncertainty in geological interpretation — another aspect we need to be aware of in the sort of science communication issues that Iain Stewart was telling us about.

Having assembled the Southwest through plate tectonic shufflings, the Southwest's Permo-Triassic history of continental weathering and deposition in an intraplate setting was revealed by Richard Scrivener and Sarita McVicar-Wright. They showed how stratigraphy, radiometric dating of interbedded volcanic rocks and a lot of careful field work placed these red beds and their record of desert and alluvial environments in the correct time-frame. Later in the day, many delegates enjoyed a boat trip to see some of these rocks' field relationships along the coast.

Frances Wall then moved us into the world where geology intersects economics, geopolitics and society by introducing us to the topic of critical metals. These are rare metals that are key components of modern technologies, but many (or all) of whose major deposits occur in places where the potential of political instability is high enough to prevent a guaranteed supply. Finding new deposits and solving technological problems relating to the extraction and recycling of these metals are therefore hot topics that place Earth science in the frontline. One critical metal is tungsten, and Frances described how some of the geological processes Robin Shail told us about have endowed the Southwest with a significant tungsten deposit — the Drakelands deposit in Devon, which is ranked as the fourth largest in the world.

The theme of natural resources and the geology that forms them was continued by Peter Scott, who demonstrated that Britain has an important mining and extraction industry, despite common perceptions to the contrary. The geological riches of the Southwest, and of the UK in general, show why Earth science is so important to the national economy.

Mark Anderson gave a wonderful tutorial on inversion tectonics. I liked the way that he used simple cross-sections to illustrate the principles of how different field relationships can develop when an area of rocks is thrust together and then extended. Mark showed how the switching of the stress fields produces field relationships with apparently conflicting or contradictory evidence for extension or compression, and how this idea of tectonic inversion can explain that. His pictures of the north Somerset coast really made me want to go there and spend time solving some neat geological puzzles on the outcrop.

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The geoscientist's toolbox is ever-expanding and it was interesting to learn about some examples from the Southwest. Chris Yeomans showed how airborne surveys from instrumentation carried on aeroplanes give us new types of observations. Clever computer processing of the data brings out new features and solve problems ranging from land use to heat production. Next, Jenny Bennett talked about how she has obtained geological information from the non-traditional sources of archaeology and historical documents to learn how and when the River Exe shifted course — a topic of immediate concern.

Investigating present-day geological conditions and real-time Earth science overlaps with atmospheric science and oceanography, as we learned from scientists from the Met Office (based in Exeter). Knowing that the Met Office co-ordinates the monitoring of volcanic ash in the North Atlantic region, as a part of a global effort for the International Civil Aviation Authority, I had the pleasure of joining Bob Maynard's trip to the Met Office on Saturday afternoon and learning of its history and operations. Felicity Liggins told the symposium how the work of the Met Office is integral to understanding many natural hazards such as flooding, coastal erosion etc. These are all that, when you think about them, are examples of surface processes familiar from the sedimentary rock record.

Lastly, Stephan Harrison challenged a lot of the currently accepted wisdom of the glaciological community by asking whether the high land of Dartmoor had been covered by ice in the last glacial period. Poirot-like, he showed us a mounting array of convincing geomorphological evidence that points to Dartmoor having indeed been the site of an ice-cap.

The symposium gave a wide-ranging review of the geology of the Southwest, the evidence for its varied geological history, and the way that geology of the Southwest make it a great place to study cutting-edge science problems such as critical metals. I thank all the speakers for giving such clear and entertaining insights. The Southwest is clearly a geologically blessed place, and I'm sure that the symposium has given locals and visitors impetus to look at the local geology for themselves.

And I thank Ann Morton for transcribing my talk, upon which this article is based.

OUGS Field Trip Reports

More Mantle in the Mountains – a further excursion to the Betic Cordillera of southern Spain

OUGS Ex-President's Trip 20 April–2 May 2016: Leader Dr Tom Argles, Organiser Jan Ashton-Jones

Authors: Hilary Black, Chris Daniel, Liz Davenport, Liam Dunne, Linda Fowler (and editor), Rhona Fraser, Sally Munnings, Isabel O'Brien, Alan Painter, Gill Toney and Tony Wallbank

Latitudes and longitudes of locations are indicated in degrees decimal; images are by the individual authors except where otherwise indicated with initials.

Introduction

Linda Fowler

The OUGS President, in addition to leading his 'President's Trip' in the second year of his term, is also invited to lead an 'Ex-President's Trip' the following year. The 2015 trip enabled Tom to revisit his PhD area around Ronda and, when the request for a further trip came up he was very happy to return to the same area. There is a full report of the 2015 trip in the *Proceedings of the OUGS* (Browning *et al.* 2016) and necessarily many locations were revisited, so this report not only focuses on new locations, but provides an additional perspective on those already described.

The Betic Cordillera is a geological domain distinct from the rest of Iberia and lacks the older basement terranes and Hercynian deformation found elsewhere in Spain. It lies at the western end of the Tertiary Alpine-Himalayan mountain belt and is dominated by folding and thrusting resulting from compressional tectonic processes. Locations visited were mainly in the Internal Zone between Ronda and the coast, in the External Thrust Belt near Antequera, and in the Internal Zone south of Granada. Much of the trip was based around the large peridotite bodies exposed in the western Betic Mountains. These have been Rh-Os dated at 1.36Ga, the date when the material moved from mantle to continental crust. This article is an account of the trip by those who took part and, while it describes the locations we visited, especially those not seen in 2015, does not attempt to explain the overall geology in any detail.

Locations are given as latitude (N) and longitude (E), in degrees decimal, taken from Google Earth and satnav data. Note that the negative longitude values indicate that these locations are west, rather than east.

Figures are by individual authors for the day in which they appear, unless otherwise credited.

Day 1 — Wednesday 20 April

Málaga Airport to Benahavis

Sally Munnings

We arrived at the first hotel in Málaga over a couple of days, some arriving on Tuesday and others on Wednesday morning. Despite a slight delay to one flight we all finally met up, as planned, over lunch at the hotel. Then, after a quick talk by Tom to give directions, we set off to see our first glimpse of the

Figure 1.1 The view of Gibraltar. This was the only day when there was rain, but the spectacular skies were worth it (LF).

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'Mantle in the Mountains', which would set the scene for the entire excursion. Because we had headed straight to Ronda in 2015 we did not see these exposures last year.

We headed west from Málaga along the coast road before turning north towards Ronda, stopping at a roadside cutting [36.498116°, –5.030946°] where we saw an exposure of a pale green rock. This was serpentinite with garnet and spinel remains; the pale green colour is characteristic of serpentinite in this area. This was helpful in identifying rocks in future exposure. The serpentinite had formed 'pods' with slickensides on each surface. Tom described these pods as 'halibuts' because of their shape, and consequently we described the rock as 'halibutised'. We also found a black mineral within the peridotite, which was identified as bastite, a serpentinite texture formed by hydrothermal metamorphism and hydration of pyroxenes. There was also a very orange mineral, iddingsite, which is altered olivine; and we also saw some unaltered green olivine.

At our turning point [36.483482°, –5.063168°] we had a wonderful view across Gibraltar to Africa at the western end of the Mediterranean (Fig. 1.1, *previous page*) and, while we were here, Tom gave us an overview of the geology we were looking at: the low lying land before Gibraltar is formed of flysch — soft sediments, which are very fertile, so used as farmland and can easily be spotted at this time of year due to the vibrant green colour of the fields. Within the flysch we could see large upstanding blocks of limestone and sandstone, some of which formed the original geological landscape around which the flysch was deposited, while others are blocks that were caught up in the deposits during tectonic activity. There was also lumpy ground in front of the flysch forming a molasse. This was derived from sediments as the mountain belt was eroded, depositing the sediment into shallow water forming red-bed deposits, alluvial fans, etc. This material varied from fine-grained muds to large boulders. Tom told us that because of the way the orogenic belt curves around, the geology of southern Spain is mirrored in northern Africa.

Figure 1.2 The leucocratic granite intrusion (LF).

We noticed a white intrusion [36.488059°, –5.062056°] and a group clambered up to look more closely at this (Figs 1.2 and 1.3). It was a weathered intrusion of leucocratic granite, which was white with small black tourmaline crystals. The granite had a very grainy texture and crumbled easily. This was because the plagioclase feldspar had been altered to kaolin, which had subsequently been washed out, leaving the remaining crystals as small grains.

We continued to Benahavis and our first, very luxurious, hotel. We met up in the evening for a short talk from Tom to cover the afternoon and explain more about the exposures seen that day. He also gave an outline of the geology we were going to see in the coming 11 days and the plan for the first full day in the field. An excellent start to the trip!

Day 2 — Thursday 21 April

Sierra Bermeja peridotite massif, Pico de Los Reales and surrounding gneisses

Chris Daniel (with Alan Painter)

Today's excursion transected the largest peridotite zone. We saw various rocks from the top of the contact zone and a small way into the overlying Jubrique Unit, some in the middle (at the col) and some just underneath the peridotite sheet (Figs 2.1 and 2.2, *opposite*). From Benahavis we headed down to Estepona on the coast and then took the MA-8301 towards the Sierra Bermeja peridotite massif. We initially stopped off at the Puerto de Peñas Blancas (col) car park, before heading down to the upper contact zone, and then stopped for lunch beside a stream. After a brief vista stop, the afternoon was spent examining the lower contact zone and a nearby augen gneiss exposure.

Figure 1.3 Fortunately material had fallen down into a gully where Ted, Liz and Tom were able to examine it (LF).

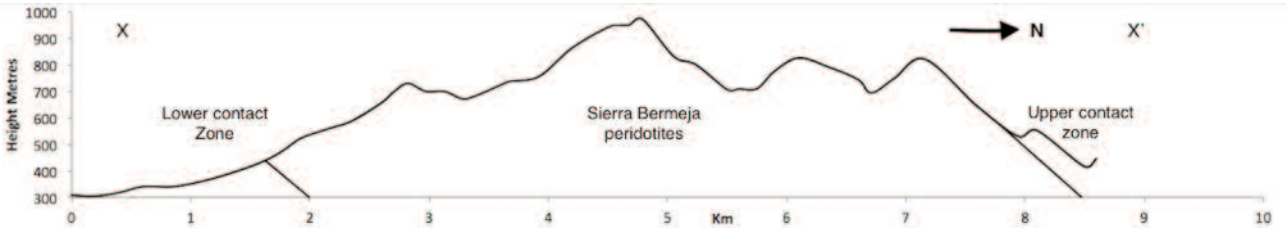


*Figure 2.1 Annotated Google Earth transect section across the Sierra Bermeja peridotite massif (*see *Fig. 2.2 for location) (after image copyright 2016 Digital Globe).*

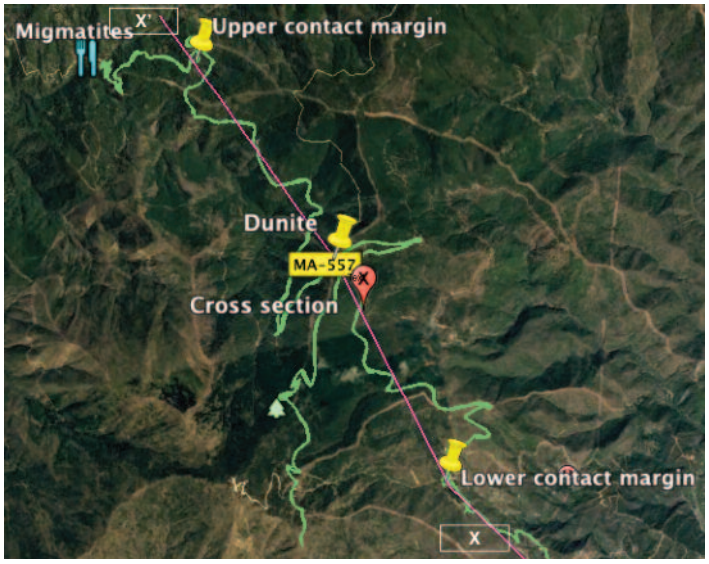


Figure 2.2 Google Earth map location overview. Line of transect in Figure 2.1, X-X[1] in purple (image copyright 2016 Digital Globe).

Figure 2.3 Weathered lherzolite (weathered to a brownish orange) found at Puerto de Peñas Blancas. The pyroxenes standing proud of the surface, and there are also small crystals of spinel.

Figure 2.4 Dunite: in this example only one or two pyroxenes are visible, together with tiny bits of spinel. The rock is otherwise predominately altered olivine (RF).

At Puerto de Peñas Blancas [36.504366°, –5.189163°], in the back wall of the parking lot, we saw different types of peridotite, mainly lherzolite (Fig. 2.3), which weathers to a brownish orange, with pyroxenes standing out proud of the surface, but also some contrasting dunite (Fig. 2.4), which is predominantly altered olivine.

The massif contains many mafic layers, in particular stringers and veins of dunite, formed by partial melts of peridotite, which have percolated upwards and through the massif. The most likely explanation is that hot fluids came through the peridotite, lowering the solidus of the originally dry rock; alternatively they may derive from decompression melting of the slab itself, but the exact role of the fluids is not well understood, as the fluids themselves are not seen, just the evidence (i.e. the mafic layers that result from the partial melting).

From here we drove down to the upper contact point [36.528501°, –5.200978°], between the top of the peridotite body and the gneiss (kinzigite) above it. This is not a ductile contact, but instead a wide gouge between the serpentinised peridotite and the crystalline rocks over it. There is a clear colour contrast between the greenish serpentinised peridotite fault gouge and the grey fault gouge from the crustal gneiss (derived from the clay minerals and feldspar); and there is very weathered kinzigite to the left (Fig. 2.5).

Figure 2.5 The upper contact zone between the peridotite body and the crustal gneiss.

The mineralogy of kinzigite is anhydrous; it is mainly composed of garnet, cordierite and sparkling bits of graphite and sillimanite which represent the restite or residue after the dehydration reaction melting of the crystalline rocks. The melt produced from this reaction has a felsic composition, which could crystallise as leucogranite, similar to that seen on the first afternoon. At the contact location the feldspars have rotted, the iron-bearing minerals have rusted, and you can crumble the kinzigite gneiss in your hand (Fig. 2.6, *overleaf*). Many samples of kinzigite had lovely lilac-coloured garnets; these are magnesium rich, indicative of high temperature and high pressure granulite facies.

Figure 2.6 Well-rotted kinzigite from beside the upper contact zone — easily crumbled by hand.

There are strong foliations in the crustal gneisses and peridotite, which is parallel to the contact in both cases. Tom is confident that this shear fabric is related to emplacement of the peridotite into the crustal rocks, an event that probably took place between 40–50km depth in the Earth's crust, possibly near the crust's base.

A short distance from the contact zone a little farther down the hill, we paused for lunch near a stream [36.530855°, –5.213205°] containing float made up of kinzigite, peridotite and very nice migmatite samples. This area is located in the next zone out from the contact, part of the Jubrique Unit, which is part of the Alpujárride Complex. We saw evidence that melting took place in the migmatite zone: melt 'frozen' in the migmatite, with clearly visible streaks of leucogranite that had melted *in situ* but never made its way out of the rock (Fig. 2.7).

Figure 2.7 Tom explaining streaks of leucocratic granitic melt within migmatite.

Re-tracing our steps to Estepona, we stopped at the lower contact point [36.478540°, –5.180832°] to examine an exposure of augen gneiss, very granitic in composition, with some cordierite. This formed at high temperatures but low pressures; we observed strong fabric wrapped around two xenoliths of foliated gneiss, showing that the foliation must have predated the melting of the gneiss (Fig. 2.8).

An enjoyable and interesting day. (However, one passenger in car 5 was a little perturbed when we managed to lose the convoy within 10 minutes of starting out; but our ability to tail the leading car improved as the journey progressed, and he relaxed, but was disappointed we could not manage a beer and coffee at lunchtime!)

[Thank-you to Isabel O'Brian for the audio recording of Tom's evening debrief.]

Figure 2.8 An exposure near the lower contact zone: augen gneiss of granitic composition (RF).

Day 3 — Friday 22 April

Pujerra area to Ronda

Rhona Fraser

This day was essentially the same as Day 3 of the 2015 field trip (Browning *et al.* 2016), except that we began from Benahavis rather than from Ronda. That report is now brought up to date with the addition of some new photographs.

Location 1

Figure 3.1 (top left) Looking towards the Sierra de las Nieves from the first stop. The bare hillsides are Dorsale Limestone, the wooded slopes are on peridotite.

Location 2 [36.626028°, –5.077827°]

Figure 3.2 (middle left) The carbonate/peridotite contact.

Figure 3.3 (bottom left) Mylonitic carbonate.

Figure 3.4 (top right) Peridotite with mantle foliation.

Lunch stop [36.598907°, –5.142078°]

Figure 3.5 (middle right) At the lunch stop, showing peridotite (brown) and leucogranite (grey) contact.

Figure 3.6 (bottom right) At the lunch stop, another view of the peridotite contact with the leucogranite.

Igualeja [36.632859°, –5.118265°]

Figure 3.7 (previous page, bottom right) The restaurant by the Río Genal in Igualeja.

Day 4 — Saturday 23 April

Cueva de la Pileta, Benalauría

Liam Dunne

From our new base in Ronda, we headed first to the Cueva de la Pileta [36.691345°, –5.268587°] (Fig. 4.1). Although used in prehistoric times, the cave was rediscovered by José Bullón Lobato in 1905. There was an opening in the rock known to locals from which bats would emerge in the dusk. However, there appeared to be a perilous drop and people had kept away until José braved the abyss, in search of the abundant bat droppings (guano), which he figured the cave would contain and would be perfect for his farm. His family have been custodians of the cave ever since. We were led in through a low opening, through a sturdy iron gate to keep out unwanted visitors — of which there were many in the early years, as local gossip was that the cave contained hidden Moorish treasure. No photography is allowed inside, in order to preserve the art work. We shared lanterns in pairs.

I have seen one or two caves in my time but this one had the most chambers and more numerous pillars, stalagmite and stalactite formations than I have encountered before. There are steps chiselled into the floor — by Bullón — to help climbing some slopes in the caverns; and some handrails. One formation has an interesting story: it was named 'the Organ' for its numerous pipe-like pillars, which make different sounds when struck. When recording in Gibraltar The Beatles visited the caves, and Ringo Starr even sampled the sounds. (The Beatles were renowned for using obscure noises to enrich their music and give it depth.) Another 'British' connection was a visit by Colonel Willoughby Verner. Born in Ulster and badly wounded in the Boer War, he lost the use of one leg and relied on a stick to walk. He visited the area in 1909 in search of choughs (a red-legged and beaked crow). He was reluctantly allowed to take some bone remains from the cave for analysis, now in the British Museum.

Figure 4.1 The group entering the Pileta cave.

Some artwork in the cave has been roughly dated to *c*. 25,000 years BP with subsequent habitations and associated art at varying times up to *c*. 4000 years BP. Carbon-14 (14C) dating has been carried out using fire soot produced when the caves were inhabited and correlation can be made using calcium deposits precipitated above and below the soot. Red, yellow and black pigments were used, and certain colours appear to be associated with different habitations. There are elegant drawings of horses, bulls, goats, snakes and fish. Other drawings are of shaman-like figures, male and female forms, and hunting. There are also primitive 'maps' of the caves and possible 'calendars' (Fig. 4.2). A large fish painting is thought to be a halibut, and is an amusing reminder of the 'halibut tectonics' with which Tom described shearing and slickensides in the serpentinised peridotite *(see above)*. We asked why there were so few cave drawings, given the long habitation time, and were told that there are many more, but they cannot be clearly seen without tools such as UV light.

Figure 4.2 Sketch of the large halibut, a goat's head and some possible calendars.

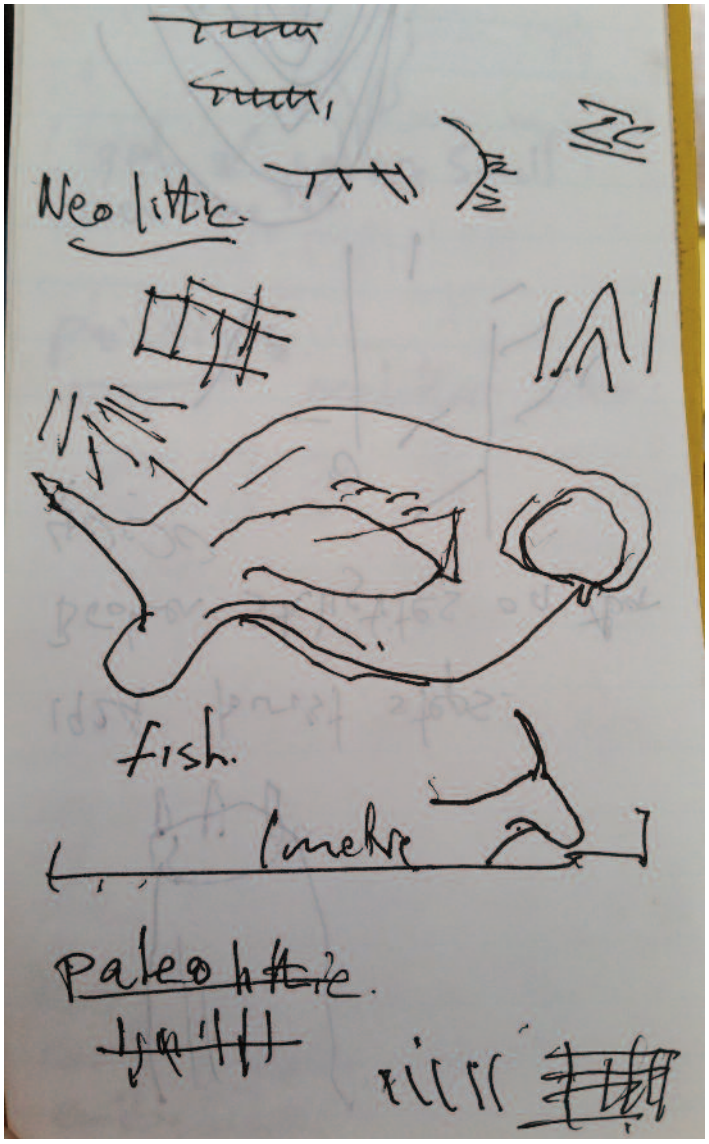


Figure 4.3 Source of the Río Genal in the Arroyo de Anicarrán, Igualeja.

Earthquakes have affected the cave, snapping off some formations. By dating the deposits covering the fallen pieces of one such it is possible to date the damage to the Lisbon earthquake of 1755. There are also water-level marks around some parts of the cave, thought to be from a lake that filled most of it, but drained away after an earthquake opened up cracks.

After our cave visit we visited surface exposures of the Alpujárride Complex, which directly overlies the peridotite seen the previous day. The first stop was a road section of strongly folded phyllites and sandstones, part of the Benarrabá imbrications at Benalauría [36.594572°, –5.270558°]. These appeared to be turbiditic in nature, with compositionally and texturally immature sandstones from a proximal source. Farther along the road section we found mudstones that must have been deposited in anoxic conditions with signs and smells of sulphur in the rock.

We stopped for lunch by the Río Genal, which has its source at the cave beside our coffee stop on the previous day (Fig. 4.3). We then travelled towards Jubrique [36.567001°, –5.228095°] to see the Jubrique Unit with its metamorphic isograds. These isograds were once interpreted as a contact aureole caused by the intrusion of the peridotite slab because they occur so close together. Phyllites into granulite facies occur over a distance of *c.* 4km, which is extremely short — in 'normal' Barrovian metamorphism this would usually occur over tens of kilometres. This shortness implies that the whole sequence has been thinned by a factor of about 10 by the extensional deformation that exhumed it.

There are many mineral associations within this unit that paint a picture of its history. First, phyllites give way to andalusite schist, which gives way to garnet schist. There are also many quartz veins (Fig. 4.4), which have been stretched and show beautiful boudinage. Some of these had begun to develop plagioclase, felsic-mafic separation that can develop into a granitic melt over time. Kyanite, which shows the high metamorphic grade to which these rocks have been subjected, has been seen to retrogress to andalusite, and the andalusite to quartz and white mica in the presence of water. This preserves a record of the deep burial and subsequent exhumation of these rocks. There are small layers of rock within this unit that appear to contradict the overall story, with porphyroblasts of minerals that should be foreign to that particular metamorphic zone. However, closer inspection of these layers shows that the growth of porphyroblasts was due to local compositional differences rather than to metamorphic grades.

Extension direction can be ascertained from lineation on foliation surfaces. There is also evidence of north-east ductile shear. Tom explained this extension using the 'cow pat' analogy: the mountain-building process grows higher until it collapses under its own weight, sliding laterally (in this case north of the Betics and south of the Rif Mountains), causing extension, even becoming concave.

Figure 4.4 Boudinage in a quartz vein in the Jubrique Unit.

Day 5 — Sunday 24 April

Morning — Taco Gorge and Montejaque

Hilary Black (with Gill Toney)

Many of us walked from our hotel to Ronda's 'New Bridge' (dating from the 18th century). Puente Nuevo separates the old and new parts of the city and overlooks Cerro Tajo Gorge (impressive at 120m deep and up to 68m wide).

Tom described the rocks we could see in the gorge: Miocene (Upper Tortonian) sandstones deposited 8–10Ma ago. They form the Tajo Formation, which is not extensive and is only found in the gorge and part of the nearby Ronda Basin. It is a cross-stratified, clastic deposit of conglomerate at the bottom and fining up into sandstones towards the top. The clasts include some from the basement, which must therefore have been exposed by that time. They are proximal fan deposits laid down in a restricted, shallow marine basin during extension and subsidence of the Alborán Sea some 8–10Ma ago. They contain limestone clasts and some marine fossils (Fig. 5.1). We found some shelly fragments of oysters, a clam with a bored shell, and clasts of sandstone and schist in the stones used to make the bridge (Fig. 5.2).

As the sediments were uplifted the river cut down to form the gorge. Looking into the valley beyond, it is possible to trace the inside edge of the alluvial fan (Late Tortonian) along a line of trees, beyond which are uplifted limestones, while the middle of the fan has been eroded out, leaving a flat-lying, fertile plain. Beyond this are flysch sediments that gave rise to green fields and a gentler topography.

We then walked into the gorge and a few of us followed an increasingly awkward path (Fig. 5.3) down to the bottom and

Figure 5.1 Marine fossils in the Tajo Formation (TW).

Figure 5.2 Bivalve fragments in the stones used to construct the bridge.

Figure 5.3 The Puente Nuevo and Tajo Gorge.

Figure 5.4 Hydro-electric works that supplied the flour mill.

under the bridge. Here there are hydroelectric works built to support flour mills until they were destroyed by a land-slip in 1917 (Fig. 5.4). We also saw various faults in the walls of the gorge that were filled with rubble and travertine (Fig. 5.5). Retracing our steps, we followed the main path to the valley bottom, to a café for refreshments and lunch, and meet others of our group who came by car. We also saw some fossils in the rocks on the way down (Figs 5.6 and 5.7). From the bottom we could see how the Tajo fan deposits dipped gently into the valley as ridges enclosing it.

(Liam kindly ran back up to the gorge to bring a car down for those not wanting to walk back up.)

Afternoon — Montejaque

Gill Toney

After lunch we drove towards Montejaque, a little way west of Ronda, into the Subbetic, passing through a landscape of Jurassic shallow-marine limestone blocks, which dip sub-vertically, and are surrounded by red/white Cretaceous marls formed by deeper,

Figure 5.5 Faults in the gorge walls filled with rubble and travertine.

more pelagic deposition and covered by flysch. At 36.759783°, –5.243244° we stopped to view an ill-fated dam that had been built between two blocks of sub-vertical karstic limestone, but which rarely holds water; then drove on to the Mirador del Pantano on the far side at 36.745276°, –5.253159°, where we had a good overview of the rocks of the External Zone of the Subbetic. The flysch covered foreground forms a rolling landscape with limestone olistoliths, emplaced in the flysch close to the Subbetic edge of the Ronda Basin. In the middle distance an anticline of the limestone is overlain by a thin layer of Cretaceous

Figure 5.6 Fossil burrows in the path down the gorge.

Figure 5.7 Fossil bivalve in the path down the gorge.

Figure 5.8 Overview of field area at Montejaque: almost vertical limestone fold limb on the right, flysch in the foreground and sandstone capping hills (marked by vegetation change) in the distance (LF).

marls and extends more than 100m. Beyond the anticline, above the flysch, and noticeable by a change in vegetation, is a hillside of horizontal, bedded sandstone (Fig. 5.8). These sandstones are generally well sorted and uniform, indicating a partly terrestrial source, part shallow marine and part desert, called the Neo-Numidian. Behind the Mirador del Pantano a small quarry contains brecciated blocks of limestone (not *in situ*), with vughs lined with calcite crystals (Fig. 5.9).

Our last stop was an exposure of Cretaceous marls [36.745108°, –5.258068°], situated low on the hillside, but contiguous with the limestone above. The marls tilt steeply, but there was only minor internal deformation. During the Cretaceous, sea levels were often high, with a mid-period anoxic event. This is reflected in the random changes in colour of the marls from red to white, indicating changes from oxic (red ferric oxide) to reduced (white ferrous oxide) conditions. We found several trace fossils of burrows and reduction spots (small pale-coloured haloes around decomposed organic material).

Across the road from this site the bedding in the marl dips less steeply and has been disrupted by a small fault.

Figure 5.9 Tiny calcite crystals lining a vugh in limestone (LF).

Day 6 — Monday 25 April

Ronda to Antequera

Tony Wallbank

After breakfast at 8 am, we left Ronda in beautiful weather, and in anticipation of new locations we drove the A-366 towards Antequera, stopping first at Puerto del Viento in the Serrania de Ronda [36.788799, –5.048535]. From here we looked back west toward the Ronda Basin, its structure more clearly visible even than from within Ronda: Subbetic limestone-capped mountains surrounded the bowl containing the town. Between Ronda and us lay green hills of flysch and orange-red Cretaceous marl (Fig. 6.1, *opposite*), which we stopped to examine; they are similar to those seen at the end of the previous day on the other side of Ronda. They form the Capas Rocas, a sequence rising above us to north and south. These marls were said to be fossiliferous but, despite an exhaustive search, nothing convincing was found; only the odd burrow and possible shell fragment (Fig. 6.2, *below*).

Figure 6.2 Layered Cretaceous marl and limestone at the bottom of track opposite the parking area at Puerto del Viento.

Figure 6.1 Looking west from the hill of Cretaceous marl south of Puerto del Viento, across to the Ronda Basin from Puerto del Viento. Note the red marl exposed near the road.

To north and south the Subbetic Jurassic limestone, which should have been underneath our position, topped the mountains (Fig. 6.3). We wondered whether the whole sequence had been inverted, or if faulting, dropping our position relative to the older rocks, or perhaps thrusting, was the explanation? We were right on the eastern edge of the Ronda Basin, in an area likely to have been subject to the same movements that had created the whole basin. It was difficult to assess the cause from where we stood, so we gradually moved up the marl hill situated south of the pass, all the time continuing to search for fossils. Only on reaching the flatter area at the top did our focus change. Here, harder limestone layers are prominent, weathered into a nodular surface,

Figure 6.3 General view from top of Cretaceous, red marl, hill of red marls around the area of the Puerto del Viento and Subbetic limestone higher up the hillside.

Figure 6.4 (top left) Fold in Cretaceous limestones at Puerto del Viento; (middle left) looking east showing close-up of part of fold structure at Puerto del Viento; (bottom left) aerial view of folding at Puerto del Viento (Google 2016).

with eroded softer marls in between. The overall antiform was covered in spectacularly eroded parasitic folding. Tom got quite excited at the find and tried to arrange the group along the axis of the fold (north–south) for a photograph, but it was not easy to capture the complex structure. We saw a hinge-like chevron with curved folds farther out (Fig 6.4, *top and middle*). The complex fold structure in these limestones can be seen on Google Maps, although the vertical dimension is flattened by the perspective (Fig. 6.4, *bottom*).

Feeling happy with the folding we had seen, we drove past El Burgo through the Sierra de las Nieves along twisty roads past more spectacular folds. Around El Burgo olive trees grow on the flysch. Then we climbed again, this time into an area of metamorphic rocks. Where the ground is not cultivated, pine trees are the dominant vegetation. We passed the town of Yunquera and more olive groves. A little farther on, after a coffee and fuel stop in Alozaina, we turned down a side road to Stop 2 (Fig. 6.5).

Figure 6.5 Coffee stop in Alozaina with a view of the general setting of flysch in the valley, pine trees on the middle slopes and Subbetic limestone and marbles forming the mountain peaks.

Stop 2 was a road cutting and stream bridge on the A-366 south-west of Alozaina [36.719891, –4.871557]. Here the predominant flysch changes to an exposure of conglomerate for a short distance. We examined the south end of the conglomerate exposure, comprising poorly sorted and angular clasts. Closer inspection showed that most were of low grade metamorphic rocks, such as phyllite and schist, some containing andalusite and sillimanite along with quartz, feldspar and biotite; there were also a few marble clasts. There were some signs of stratification, and it appeared that the deposits had been caused by transient flooding, although this was not just a mass debris flow (Fig. 6.6, *opposite*). To the north, across the old road bridge, the clasts are coarser grained, with some banding. The grade of metamorphism is higher, with migmatites and the occasional gneiss. We saw 'foxy-red' biotite, showing likely titanium content, and then more dark-grey migmatite. Some clasts show higher grade biotite intergrown with fibrous sillimanite. At the northern end of the section the metamorphic grade is higher still, with kinzigite containing garnets (Fig. 6.7, *opposite*).

We discussed whether or not the original bedding was inverted, perhaps as a wadi eroded an upper, less metamorphosed (cooler) source first, although there was no visible evidence that rocks exposed at the southern end of the road cut were younger, so this idea remained speculation. In this respect we were less convinced than the previous year's trip had been of the relative ages of the different ends of the section (Browning *et al.* 2016). Tom said

Figure 6.6 Southern end of exposure at Alozaina, showing stratification and angular clasts.

that the flash floods eroding the Maláguide and Alpujárride formations, some distance above us, which produced the deposits we were studying, were not related to the present-day stream now cutting down through them.

Stop 3 was at a road cutting near Valtocado on the A-7053 [36.596173, –4.705536]. Here we saw peridotite, much as we had seen at several locations on previous days, in close contact with gneiss. The two were separated by a steep, normal, late, brittle fault, containing fault gouge and cataclasite, *c.* 300mm wide (Fig. 6.8). The peridotite was serpentinised in places, especially near

Figure 6.7 (left top) Large clast of migmatite on the north end of an exposure in the Alozaina Formation; (right below) typical clast from the northern 20m of exposure at Alozaina, showing course-grained, banded gneiss.

Figure 6.8 Fault contact between weathered granitic gneiss and peridotite, near Valtocado.

the boundary. We were close to the edge of the peridotite massif, where late faulting caused chunks of gneiss and peridotite to be chopped up. We were looking at the junction between two such chunks. The gneiss is granitic in origin, weathered brown, and contains kinzigite and remains of garnets (Fig. 6.9).

We continued to our next hotel in Antequera easily along the main roads with little geological interest. The much searched-for marine fossils (ammonites) were eventually found right outside the hotel in a bench made of red Capas Rocas. In the evening some of the group walked up to the Alcázar, where there are excavated Roman baths and a splendid view over the area in the evening light (Fig. 6.10, *overleaf*). We were rewarded by a meeting with Antequera's Mayor, an official welcome to Spain and Antequera and a private tour of the Town Hall, including examples of 'Antequera Marble' in white, red and black (the latter probably polished serpentinite) similar to some of the rocks we had seen during the day.

Figure 6.9 Granitic gneiss close to contact with peridotite, showing thinned, extended feldspars and weathering to brown, near Valtocado.

Figure 6.10 View east from the Alcazaba (castle) at Antequera, showing topography and the Peña de los Enamorados, a peak of limestone that looks like a recumbent face.

Day 7 — Tuesday 26 April

Carratraca area

Isabel O'Brien

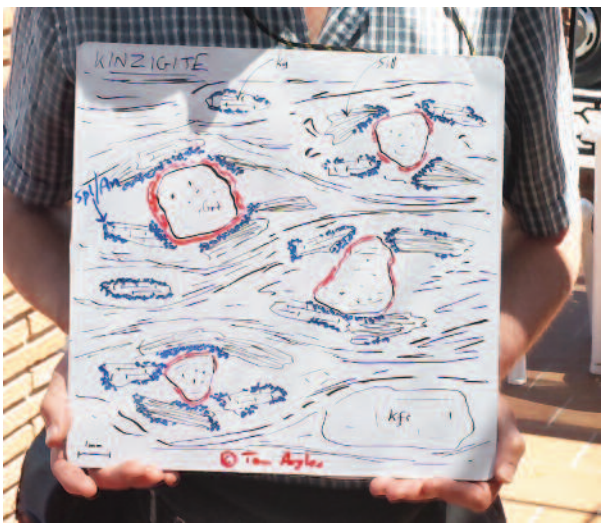
Our first stop was at a slightly different part of the summit than that visited in the 2015 trip [36.858456, –4.794682]. We observed the same 360° view around Sierra de las Aguas described in Browning *et al.* (2016, 102). We also observed that the flysch occurs quite high up as well as lower down in the landscape. There is a real topography to it since its thickness varies considerably. A popular Andalusian saying, "en medio como el miércoles", alludes to something that is annoyingly in the way — much like the flysch that we saw popping up everywhere — between the peridotites, granulites, phyllites and gneisses. Thereafter, we made jokes about this with phrases like "flysch is like Wednesdays" and "in the middle like flysch".

The spotty leucogranites under our feet has tourmaline-quartz aggregates, representing the classic crustal-melt leucogranite texture. Tourmaline is a borosilicate. Crustal rocks are poor in boron, so the presence of boron indicates the likelihood of deep-sea marine sediments, predominately rich in aluminous clays, melting alongside the crustal rocks. Unlike the tourmaline in Cornwall found alongside topaz, these rocks underwent minimal melt, just about reaching the eutectic point. The phase relation of the minerals present dictates a minimal-melt composition. In the case of these leucogranites, the melt had a fixed composition of K-feldspar + quartz, plus very little, if any, plagioclase. Tourmaline formed from mopping up all the boron in the melt.

At our next stop [36.857242°, –4.811306°] we walked past the narrow strip of kinzigites and arrived at the transition zone with migmatite outcrops, the rocks that 'froze' in the act of melting. Although we had left the bulk of the garnets behind with the kinzigites, Liz Davenport found a beautiful deep violet garnet with a green rim around. It was a pyrope garnet rich in magnesium as inferred by its deep colouring, with an altered cordierite rim, or corona. Pyrope garnet has its origin in ultramafic rocks, usually mantle-derived peridotite. A corona of altered cordierite in garnet forms by decompression reaction and reaction texture. The garnet is brought up from depth to about 10–12km from the surface, with lower pressure conditions but approximately the same temperature, if not slightly higher (750–800°C). Cordierite is a low-pressure phase mineral that grows around the garnet in a reaction texture. A reaction texture forms between the garnet and the kyanite and sillimanite that surround it. The double coronas are seen in thin section, and their presence is evidence that high temperatures persisted after the deformation event ended. In these two-stage coronas, cordierite is found around the garnets, surrounded by intergrown symplectite, hercynite spinel and anorthite.

We stopped at Bar El Trillo in Carratraca for refreshments and a lecture in kinzigites under the microscope, expanding on the story told around the beautiful garnet previously found. Tom hand-drew a full-colour 'thin section' (in plain polarised light!) of a kinzigite, although he lamented not having a green pen for the hercynite coronas (Fig. 7.1). Some of the big garnets have specks

Figure 7.1 Tom's drawing of a kinzigite in thin section (LD).



in them, which are inclusions of minerals. Assemblages like biotite, ilmenite (in the edges), rutile (in the core), plagioclase feldspar and muscovite act as markers of the early pressure-temperature history during the garnet's formation. The outer parts of the garnet outgrew the strong, foliated fabric that wrapped around them, containing biotite and sillimanite. There are also three types of large porphyroblasts: K-feldspar, kyanite and sillimanite. Some of the sillimanite is present in rafts wrapped around the garnets while further sillimanite forms sheets and aggregates that replace the kyanite because they are both polymorphs. All these minerals grew during crustal thickening as the rock heated up to *c.* 750°C and was buried to depths of 40–50km, marking the peak assemblage. Then the mountain belt started to collapse, with a drastic thinning of the whole section that rapidly decompressed the gneisses. The minerals became unstable during the exhumation process. The main reaction occurs in the garnet and the aluminosilicates. These minerals rely on moderate to high pressures, and so they start to get replaced by new minerals as the decompression progresses.

The double coronas are composed of an inner skin of cordierite and an outer fuzzy intergrowth between hercynite (a very dark green iron spinel) and anorthite (a calcium-rich plagioclase). This fuzzy coating can also be found around the other porphyroblasts, and it is due to the transfer of ions and elements from one phase to another. Cordierite in thin section often looks orange because it starts to alter, which helps in the identification of what, otherwise, would be a colourless mineral, much like quartz. Also, cordierite often shows zircons with pleochroic halos, another feature that distinguishes it from quartz.

Figure 7.2 Schlieren of gneiss on leucosomes, Arroyo de los Cañas.

The third stop brought us to the Cerro Tajo extensional fault [36.821643, −4.795731], where we looked for the mysterious xonotlite mineral in the serpentinised contact rocks (Browning *et al.* 2016, 103). It must have been because of the unforgivingly hot sun that we did not find a sample of the elusive xonotlite; instead, we saw plenty of chromite, lherzolite and lovely 'halibut'-shaped peridotite.

The fourth stop was at Arroyo de las Cañas, a lay-by wedged between the A-357 and the river [36.810835, −4.782613]. (Note: both our 2016 trip Itinerary and last year's report incorrectly give the name as Arroyo de la Cala). There is an outcrop of migmatitic crustal gneisses intruded by leucogranite and leucosome. A peridotite face rises on the far bank of the river. It seems that the river has taken advantage of the fault at this location. The migmatitic crustal gneisses are extremely crumbly due, Tom asserted, to the amount of hammering inflicted upon them by geologists! The leucogranites, speckled with tiny garnets and tourmaline, are formed at a higher pressure than the ones seen earlier that day. The leucosomes show wispy structures of gneiss (Fig. 7.2) called schlieren, composed of biotite, feldspar and sillimanite that follow the same sense as the fault. There is cordierite in the gneisses, plus large amounts of secondary muscovite, suggesting that it happened in a later event that created structures such boudins or veins. Tom drew our attention to the garnets in the gneisses: almandine garnets, rich in iron, blood red in colour and quite large. In the leucogranites, spessartine garnets are more numerous and sub-millimetric in size. These are rich in manganese, not uncommon throughout the Betics and the Himalayas; they have a magmatic origin, crystallising from eutectic melts of other crustal rocks. There are also some large, blood-red garnets in the leucogranites, but they originate in the gneisses: as the gneisses melted, the garnets were freed but not consumed, ending up, unmelted, as xenocrysts. These garnets act as time capsules recording the metamorphic conditions of formation.

For our final visit, instead of stopping at Sierra de Alcaparán, Punto de interés geológico, we had the choice of driving home taking the fast route, or through the scenic flysch landscape, where we could stop at a new location by a road cut. All except for one car decided to go 'flysching'. Taking the A-343, we drove through Álora and stopped north of Valle de Abdalajís, arriving at a colourful, fresh road-cut [36.970305, −4.678146] (Fig. 7.3, *overleaf*). On the way there, we passed Cretaceous marls plastered up at the sides, Jurassic Subbetic limestones, with their distinctive red and white strata. The new outcrop, however, was a bit of a puzzle as it lacked these features. The sequences are offset by several faults, showing a rather deformed stratigraphy of sandstones, limestones, and multi-coloured marls. We were dealing with a Triassic Subbetic block. Tom was thrilled with the finding, as he had never seen anything like it in the Betic External Zone. But we came to a surprise feature protruding out of the flysch: a strongly sheared, finely banded block of gypsum containing, possibly, anhydrite and aggregated gypsum crystals (Fig. 7.4, *overleaf*). Some parts show sugary textures (Fig. 7.5, *overleaf*). Its unusual shape, similar to the open mouth of a shark, appeared to be the cross-section of a sheath fold, just over 1m across its widest part. In the Betics, gypsum and anhydrite tend to sit at depth, in horizons that facilitate the movement of the orogeny's detachment zones because it is the weaker layer. That gypsum block simply looked like part of a mélange, caught up in the tectonic event and brought up to the surface.

Figure 7.3 (above) Triassic Subbetic marls and sandstones in a road cut north of Valle de Abdalajís.
Figure 7.4 (left) Finely banded gypsum boulder, just over 1m high, in the flysch.
Figure 7.5 (below) Sugary texture and fine bands in the gypsum boulder.

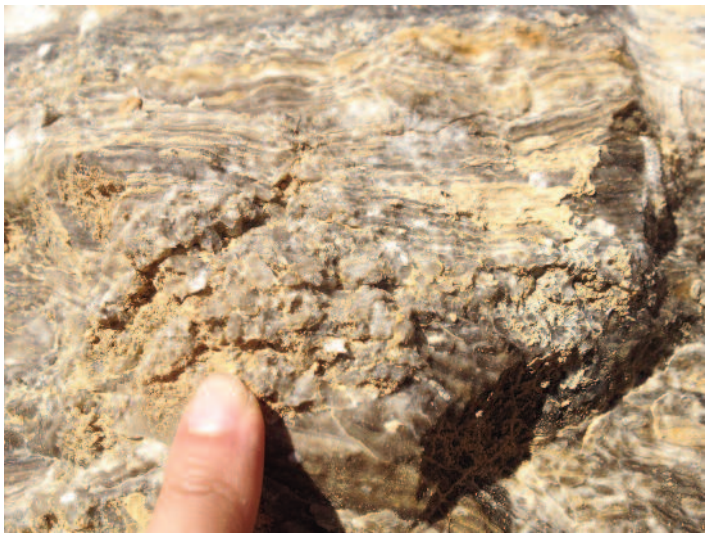


Figure 8.1 The grey rocks out-cropping in the middle of the photo are the Jurassic limestone (LD).

Day 8 — Wednesday 27 April

The Maláguide nappe, Bobastro, El Chorro and Arroyo del Colmenar

Liam Dunne and Isabel O'Brien

The first stop was at a road-cut [36.896847, −4.826426], at the southern end of the Embalse del Conde de Guadalhorce, one of three large reservoirs west of Antequera. This road-cut reveals more Cretaceous red and white pelagic marls with microfossils, deposited above the calcite compensation depth (CCD). They are part of the weakly metamorphosed Maláguide nappe, which comprises sediments from the Eocene all the way back to the Silurian. The location was particularly interesting because all these periods can be found in sequence in a space of just over a kilometre. The marls run into an apparently thin layer of Jurassic limestone, which is pinched out completely at one point, enabling sediments from above and below it to come into contact (Fig. 8.1).

Next, we walked along a river bed of the Arroyo de la Zahúrda (meaning pigsty stream!), in which we examined the next beds in the sequence: Permo-Triassic red sandstones and conglomerates. The conglomerate contains lidite, a variety of black chert (Fig. 8.2). These Triassic sediments belong to the Internal Zone, unlike the Triassic Subbetic multi-coloured marls that we saw the previous day in the External Zone.

There were paler patches in the red sandstone, possibly caused by reduction around decaying matter in the fresh sediment. Fluctuations in the water table would create these conditions that, together with some cross laminations also seen, could have been created in the flooding plain of an alluvial depositional environment. Farther along the river bed, we encountered grey sandstones. They are coarse-grained and contain mica flakes, inferring a proximal marine depositional environment (Fig 8.3). All these sediments are Upper Carboniferous in age.

Figure 8.2 Triassic conglomerate with lidite (IO).

Figure 8.3 Large, silvery metamorphic mica at the tip of the thumb (LD).

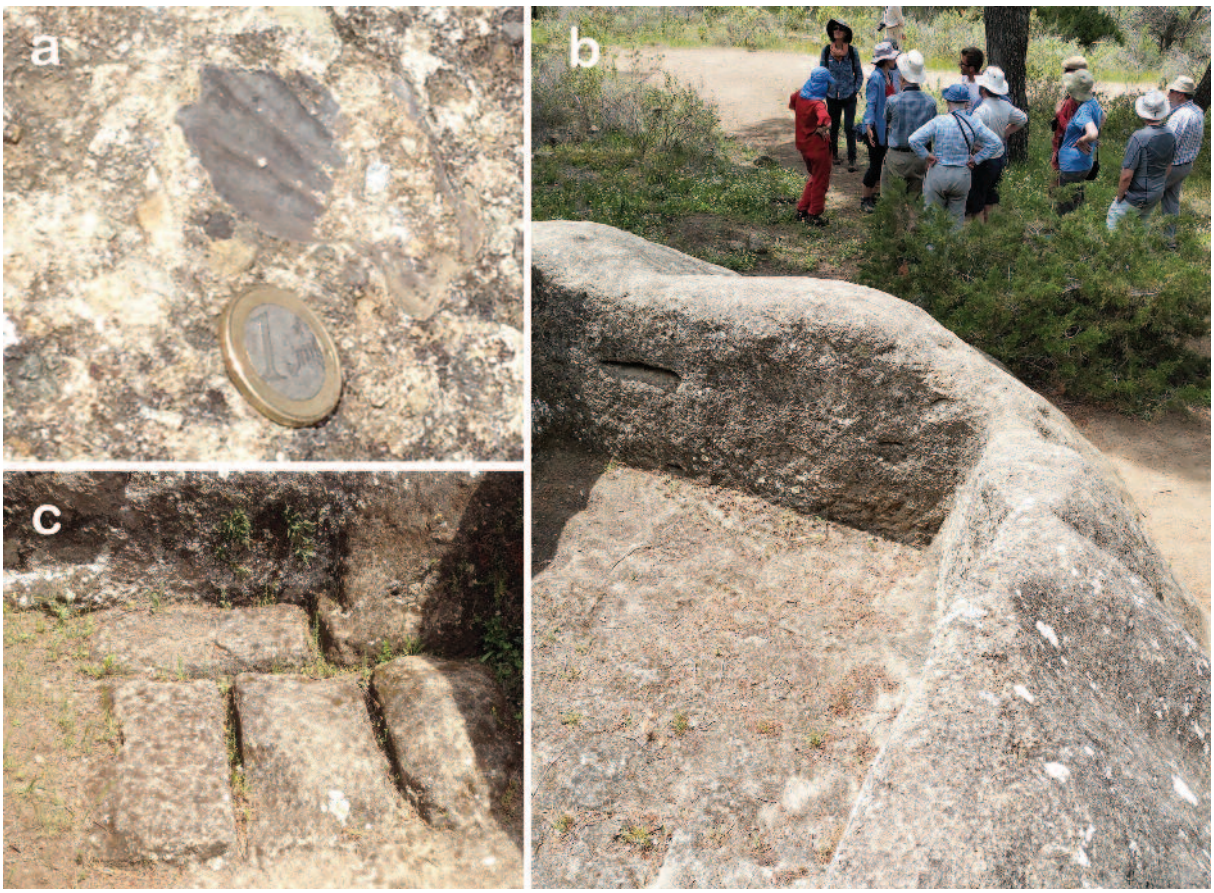


Figure 8.4 (a) Pecten on the Tortonian sandstone (IO); (b) silo for storing grain (LD); (c) ashlars traced on the bedrock (IO).

Liam found a rock with some mica of metamorphic origin wrapping around other grains (Fig. 8.4), evidence of a tectonic fabric from an earlier orogeny, most likely the Hercynian rather than the Alpine orogeny, as the other sediments in this nappe haven't been metamorphosed to the same grade. We walked through continuous sediments from the Cretaceous right back to the Upper Carboniferous over a distance of less than a kilometre. The emplacement of this nappe has very much attenuated the sequence, which is what caused the Jurassic limestone bed, mentioned above, to pinch out. If we had continued along the riverbed, Tom assured us, we would have encountered Silurian and Ordovician rocks. We took Tom at his word and turned back, as it was lunch time and hunger called.

After lunch by a pine forest, we drove towards the large sedimentary mountain that had been in view for the last few days, comprising layers of sub-horizontal Tortonian sandstones. Viewed up close we could see magnificent metre-scale cross-stratification, reminiscent of cross-stratification in desert dunes. The grains were much too large to be wind-borne, however, and upon closer inspection we could see abundant marine fossils in the sediments.

At 36.899732, –4.780502 we arrived at the entrance to Bobastro, the site of a small city built on a mountain and carved out of the sandstone. Now in ruins, the settlement was developed in 880 CE by rebel leader Omar Ibn Hafsun. Opponents to the Khalifa ruling in Córdoba, Omar and his followers gathered and lived in Bobastro until its destruction by Abd-ar-Rahman III in 928 CE. Our entry tickets included a guided tour of the ruins, situated half way up the mountain and reached by winding stairs carved out of the sandstone, in which we spotted many fossils, such as Pecten, barnacles and corals (Fig. 8.4a).

Cristóbal Baeza, the guide at Bobastro, explained the geographical importance of establishing the city in such a place. He showed us the panoramic views seen from that vantage point. To the south is the Sierra de las Aguas, the peridotite massif we visited the previous day, which takes its name from the abundance of aquifers that emerge from it, supplying water to Ardales and Carratraca. To the south-west is the Sierra de Alcaparaín, a limestone massif with its tallest point, Pico del Grajo, at 1,332m; the Sierra de Ortegícar is to the north-west, with two towns seen beyond the flysch: Cañete la Real and Teba with its castle. To the north and obstructed by the mountain top are views of the Sierra de Huma, Jurassic limestones with ammonites.

The abrupt terrain surrounding the mountain made Bobastro a natural fortress for Omar, who eventually converted to Christianity, changing his name to Samuel. In this strategic location, the 3km of available land once sheltered among 1,500–2,000 inhabitants, and Bobastro became the capital of the rebellious movement against the Moorish occupation. A wall was built around the city, but few structures remained after its destruction. There was a church in the monastic settlement, also carved out of the sandstone. According to recent archaeological investigations, the natural cracks on the rock halted the construction of a much bigger building, which was eventually erected beside the Alcázar at the summit. Beside the church, there was a hole in the ground, the drain that leads to the *aljibe* (water cistern). Such cisterns are found throughout drier regions in Spain to store water, for example rain collected from the roofs of buildings placed around a square, draining to a central courtyard. The courtyard itself has a gentle angle towards the drain in the centre. An endemic newt, *Pleurodeles waltl*, is usually thrown into the *aljibe* to keep the water clean; and as sandstone is permeable,

the interior of such cisterns are coated with red clay. Other room were excavated in the rock for grain storage (Fig. 8.4b), and the excavated material used as blocks for other buildings. The size of these blocks, or ashlars, was 'one arm long by one elbow wide' (Fig. 8.4c). We did not have time to continue our climb to visit the castle and a modern reservoir, Embalse de la Encantanda, an engineering marvel built on the mountain top. We thanked Cristóbal for his time: he had by then had taken an interest in our hand lenses and wanted to know more about the fossils in the Tortonian sandstones that he was so keen to show to future tourists.

After a short drive through a narrow, jaw-dropping sandstone gorge (and a very close encounter with a speeding bus!), we stopped at Bar La Ermita, Tom's base during his PhD work in the area [36.913455, –4.781827]. The vertical sandstone walls, with their sinuous forms, were the perfect nesting place for vultures and an adequate setting for our next geology lecture. With the aid of another of his hand-drawn sketches (Fig. 8.5), Tom explained that, during the Tortonian, the Atlantic Ocean was linked to the Tethys Ocean through two or three narrow seaways connected through the Guadalquivir Basin. This would account for the size of the bedding forms, as the currents would have been quite strong through these seaways. It is also evidence for relatively high sea levels. The process is well described in Browning *et al.* (2016, 104). This was the site of what geologists call the Strait of Málaga. The sandstone here contains clasts of all rock types from the Internal Zone, such as peridotite, a sample of which was found by Liam. Tom was delighted, as it provided evidence that the whole mountain belt had already been exhumed by Tortonian times.

Figure 8.5 Tom's field sketch depicting the unusually vertical unconformity between the Tortonian sandstones (in red) and the Jurassic Subbetic limestones (in black). Manmade structures such as the road and old dwellings in the cliffs are depicted in blue (IO).

Figure 8.6 Vertical unconformity between the Palaeozoic limestones (right) and the Cenozoic sandstones (left) (IO).

We made a quick stop 500m from the bar [36.913378, –4.775382] to see the almost vertical unconformity between the sub-horizontal Tortonian sandstones and the practically vertical Jurassic Subbetic units (Fig. 8.6), a contact so striking that we include a Google Earth view as well (Fig. 8.7, *overleaf*).

We then continued towards El Chorro. This area is known as the 'lake district' of Málaga after the beautiful reservoirs created when the Río Guadalhorce was dammed. A walkway called El Caminito del Reyis pinned to the wall of a gorge. The walkway was constructed at the start of the 20th century to provide access for the hydro-electric power plant workers. When King Alfonso XIII used the walkway in 1921 to inaugurate the Conde del Guadalhorce dam the route got its present name. It had fallen into disrepair and was closed to the public until recently, although this did not stop many daredevils from taking a chance to walk along it. It is now fully restored and open for tours. From our viewing side, we could see the engineering structures that connected the Embalse de la Encantada on the top of the mountain, to the dam below. Water is pumped up at night to be released during the day, producing electricity.

Figure 8.7 A Google Earth image showing the sub-horizontal sandstone unit (bottom-left) and the vertically tilted limestone unit (top-right). The star marks the observation point (Google Earth).

Our final stop was the Arroyo del Colmenar to view a nappe of Alpujárride rocks [36.894578, –4.752534]. These rocks are a higher metamorphic grade than the Maláguide Unit we were examining earlier. They comprise highly deformed psammites and schists containing andalusite, kyanite and sillimanite. The sandy layers pick out the original bedding and remain largely unchanged, although garnets can sometimes form in these layers. The amount of compression can be seen where these sandy layers have been folded asymmetrically. Tom made a sketch to demonstrate how the shorter limbs are squeezed and incorporated into the longer limbs, a feature he has never seen elsewhere.

Day 9 — Thursday 28 April

A guided visit to El Torcal

Isabel O'Brien

Our first stop of the day was at a road-cutting along the A-45 motorway, south of Antequera, to see the Málaga dykes in the Maláguide Unit [36.879575, –4.427819] (Browning *et al*. 2016, 105). Then we drove to El Torcal de Antequera [36.952532, −4.545014] where it was surprising to see so many people, cars and buses at the top! We went straight to the Visitor Centre's restaurant where we had booked lunch for the group. We also had time to walk about the Interpretation Centre to learn more about the geological processes that formed the karstic landscape, well explained in Browning *et al.* (2016, 106–7).

Our visit was guided by a local enthusiast, Jorge Muñoz González, who understands the real beauty and importance of El Torcal.

(Jorge works as a manager in the 125-year-old La Antequerana bakery, which holds one of Spain's oldest *mollete* recipes: *molletes* are a traditional soft bap that Tom introduced us to during the trip. A mutual friend of Isabel and Jorge had told Jorge about the OUGS trip, and he offered to lead us, so Tom and I met him the previous evening to organise the visit. Jorge arrived at our hotel by bike and we quickly got on with the planning: we were going to take the Red Route, also known as 'La Ruta de Los Amonites'.)

La Ruta de Los Amonites is the longest track and, more excitingly, a route prohibited to the general public. We were able to take it because we were guided not by just one, but by two local guides — for when we met Jorge after lunch on the 29th he was accompanied by his friend Miguel Ángel Rubio Tortosa. Jorge explained that it was Miguel who taught him all the different routes in El Torcal and that their friendship grew from all the hillwalking they have done over the years. Sometimes, a group of friends gathers on full moon evenings and, after watching the sunset from the western rim, they walk under the moonlight for a few hours. Jorge said that on such nights El Torcal is simply stunning.

El Torcal was the first park in Andalucía to be designated a Natural Site of National Interest, in July 1929, and its 17 square km were declared a Natural Park Reserve in October 1978. The good news Jorge has sent since our visit is that Los Dólmenes de Antequera together with El Torcal and La Peña de los Enamorados were declared a World Heritage Site by UNESCO in July 2016.

We saw many ammonite moulds, several of which can be seen in last year's report (Browning *et al.* 2016, 107); some of those we saw are even larger. Miguel told us that on several occasions during his walks among the karsts he heard the tapping of a hammer echoing throughout El Torcal. He eventually found the culprit, another local who has supposedly chipped out hundreds of ammonites. As a consequence, everything that we found was just a mould.

El Torcal's landscape is simply astonishing, as are the landforms that extend around the mountain all the way to the horizon. Jorge brought us to a large vertical chasm, Sima del Chaparro, and the most adventurous climbed down to see it inside. Then we reached the northern brim and walked along it for a while. There was a sheer drop of many hundred metres. The town of Antequera extended at the foot and, beyond, La Peña de los Enamorados. We finally arrived at 'El Sombrerillo', one of the iconic formations in El Torcal. Jorge invited Tom to hop on top, and surely enough, Tom did it (with some help!). It was an excellent opportunity for a group photo (Fig. 9.1).

Figure 9.1 Our group under El Sombrerillo with Tom Argles on top (photo by Jorge Muñoz). (Because the afternoon was hot and, near the start, we had to scramble up some rocks, Gill decided to head back to the shady visitor centre. Also, Jan and Linda were having a few day's break, so these three are unfortunately missing in our group photo.)

Figure 9.2 Abrigo de Juan Ramos quarryman's hut, built in 1787; note grinding trough in boulder in foreground (photo © D. M. Jones 2015).

We then walked south for a while, until we reached a structure carefully built with limestone boulders, with a wooden beam on top of a door opening. On a closer look, it was merely a wall built around the rock by taking advantage of the space below an overhang, leaving a room inside. This was a refuge built in 1787 called Abrigo de Juan Ramos named after a quarryman that lived there (Fig. 9.2). Not far from the refuge, our guides pointed at another chasm. This time, only Liam and Jorge ventured in, as it was no more than a small hole in the limestone pavement, and they disappeared into it. Jorge threw a rock that bounced off the walls several times for what it seemed an eternity until we heard a splash. Of the many chasms in El Torcal, about 100 have been explored; this one, called Sima Rasca, was the deepest at 249m.

We turned south-east and headed towards the car park to conclude the visit, not without first finding large veins of beautiful calcite crystals (Fig. 9.3). It had certainly been an amazing, safe walk around a very deserted part of El Torcal. Tom thanked Jorge and Miguel for their generous time and stories (Fig. 9.4, *overleaf*).

Figure 9.3 Veins with calcite crystals.

Figure 9.4 Tom thanking Miguel and Jorge (left to right).

Day 10 — Friday 29 April

Antequera to Granada

Liz Davenport

The morning was free and members of the group spent it differently. Some visited the Neolithic tombs of Los Dólmenes de Antequera — for a full description of which, see Browning *et al.* (2016, 106). As reported above, on July 18, 2016, Los Dólmenes, along with la Peña de los Enamorados and El Torcal de Antequera were declared a World Heritage Site! Others visited the Antequera Alcazaba; I visited the City Museum in the Palace of Nájera to explore Roman Antequera (some traces of this are visible from the square in front of the Arco de Los Gigantes). The displays here are excellent, focusing on material resources and material practices with ample graphics to illustrate contexts of use. Geology is given its due: one display presented the wide range of minerals (and their provenances) used in the *tesserae* that make up Roman mosaics in the area. Local stone was not used for prestigious domestic interiors (examples of such work are two elegant portrait sculptures of Venus and Drusus, which are made of Greek marble). There were, however, two examples of public works using locally sourced carbonate: a rather roughly hewn portrait sculpture, and a family mausoleum, a centrepiece of the Roman section of the museum.

In the afternoon we drove to Granada along the A-92 through thick deposits of Granada Basin conglomerate (thicker on the north side) as we approached the city (these are briefly described in Browning *et al.* 2016, 111). Our hotel was near the Alhambra, and after a merry dinner near by, a small group decided on impulse to explore the Alhambra Formation conglomerates (Pliocene to Lower Pleistocene), with sand and silt intercalations, interpreted as alluvial fan material. We followed the 'Cuesta de los Chinos' (Fig. 10.1) and the 'Cuesta del Chico Rey' to the east of the palace down to the Río Darro, completing our circuit by traversing the Albaicín. On the skyline, we had the floodlit Alhambra (Fig. 10.2) under bright stars, on the ground, numerous large toads, enjoying the cool of the night.

When conglomerate is seen under dim street lights, crystalline rocks (Fig. 10.3) are salient (we had noticed this in the street walls on our way to the restaurant), and it was only with difficulty that we made out microstructures and fragments of marine fossils by the feeble torchlight of mobile phones (Fig. 10.4, *opposite*). The Granada Basin is still an active seismic zone, and there is ample evidence in the conglomerate of small scale faulting.

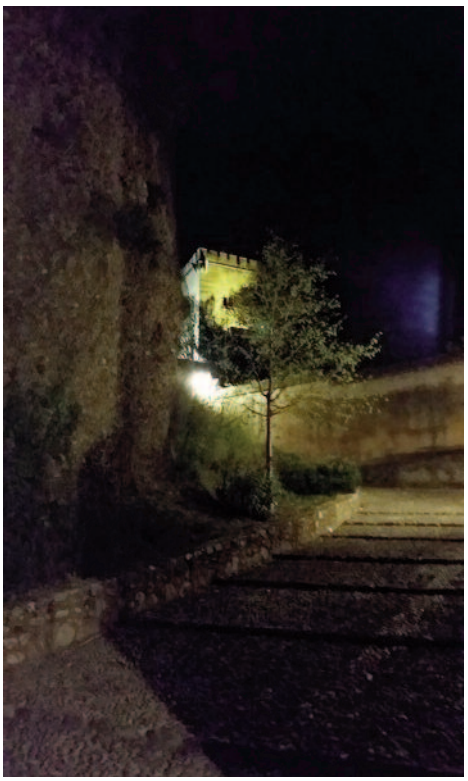


Figure 10.1 The 'Cuesta de los Chinos', Granada (PR).

Figure 10.2 The Alhambra, Granada (PR).

We did see striations and small displacements in the rocks of the northern side as we returned to our starting point. The conglomeratic formation of the Alhambra Hill reduces the amplification of seismic waves — hence the risk to the Alhambra is described as 'moderate' rather than severe (Azanon *et al.* 2004).

Figure 10.3 Amphibolite clast in conglomerate, Granada (IO).

Figure 10.4 Inspecting rocks near the Baños Romanos by feeble light! (IO).

Day 11 — Saturday 30 April

Sierra Nevada

Gill Toney

The Nevado-Filábride nappe is the lowest metamorphic complex in the Betic Internal Zone, forming the Sierra Nevada and the Sierra de Los Filábres. The complex was subducted after the other mountain building events occurred, then exhumed quite rapidly in the mid-Miocene, extensively thinned, and then highly deformed by thrusting and folding. The metamorphic grade of the nappe is complex, with evidence for blueschist and eclogite (high pressure/low temperature) events that have been overprinted by retrogressive greenschist and amphibolite grades. Divided into two units, the nappe consists of the lower Veleta Unit and the upper, Mulhacén Unit.

Starting in the Granada Basin, formed by faulting during the exhumation stage of the complex, and containing up to 1,000m of basin sediments from deltaic fans feeding into the basin during the late Miocene (7–8Ma) (Fig. 11.1), we travelled uphill through the thick Veleta Unit comprising graphitic schists containing garnets, graphite and micas. We passed roadside exposures of blocky carbonate Triassic dolomite of the Alpujárride nappe and into the Mulhacén Unit, which contains pale and dark mica schists, augen gneisses and mafic amphibolite boudins, and forms the highest peaks of the range. Because of the geometry of the thrust sheets, the farther uphill we drove the farther down the sequence we moved.

Parking at the roadside [37.112060°, –3.431919°], we walked down a road section examining a variety of highly metamorphosed schists and granites. The granite gneiss is porphyritic, containing mica, a specular haematite crystal and two kinds of garnets — Fe-rich and, unusual for garnets, small pale pink Ca-rich ones. The granite formed from crustal melt during a mountain-building stage (280–290Ma) and was strongly deformed. The section also contains crumbly, cross-cutting, foliated micaceous gneiss, green chlorite schists with biotite and more pale carbonate garnets. We observed clear evidence of strong metamorphism and deformation with late stage veins cutting across the fabric, together with sigmoidal intrusion trails in the garnets. The last part of the section is a mud slope formed from broken-down Triassic phyllites containing large deposits of coarse, fibrous satin-spar gypsum.

Our second stop was at Collado de las Sabinas [37.115149°, –3.423004°], a field location, which had not been examined in the 2015 field trip. Here we found felsic gneisses and deformed

Figure 11.1 Basin sediments are deposited thickly on the lowest slopes of the Sierra Nevada (LF).

carbonate rocks. This is a classic carbonate mylonite, which has much weaker bonds than silica. The exposure contains spectacular isoclinal folds and carbonate porphyroclasts wrapped around by the calcite matrix, the asymmetry of the curve pointing to a dextral sense of shear (Fig. 11.2).

Continuing uphill, above the ski resort, we stopped at 2,250m [37.111096°, –3.413017°] to examine a roadside exposure consisting of mafic gneisses, schists and amphibolites with eclogite relics. Mafic boudins of amphibolite facies indicate a high-pressure rock that had been subducted down to 60–80km, then exhumed slowly. The exposure raises questions as to whether it is part of an ophiolite — the mafic amphibolite derived from a gabbro protolith could be ocean floor. The schists contained chlorite, which could indicate retrograde blueschist metamorphism. Pods of epidocite (a highly altered epidote and quartz bearing rock) also suggest ophiolite origin, while garnets, mica schists and staurolite indicate mafic origins. We also found purplish-coloured minerals, which could have been copper ore and related to a major fault between the Nevado-Filábride and Alpujárride complexes.

Three-and-a-half kilometres farther up the road we stopped in the Hoya de la Mora area to eat our lunch and enjoy splendid views across the Granada Basin as far as the Sierra de Loja, 70km to the west. In the afternoon most of us visited the Alhambra, which sits on a hill of coarse-grained molasses deposits — early basin sediments deposited during uplift and redeposition.

Figure 11.2 Structures in the roadside exposure at Collado de las Sabinas (a, above) Tom explains shear sense; (b, left) Close up of porphyroclasts (area outlined in white in (a)); (c, below) isoclinal folding (LF).

Day 12 — Sunday 1 May

Niguelas, Nerja and Torrox

Liz Davenport

The first stop was the Niguelas fault [36.982136, –3.536371], for a detailed description of which, see Browning *et al.* (2016, 111). The exposed fault plane is the footwall, and striations on extension cracks here indicate that there has been more than one episode of faulting related to the development of the basin. The fault is traceable for 20km or so, and from our vantage point we could see that it takes the form of en-echelon segments (often separated by gullies) where the fault has jogged back.

The sediments that we saw on this visit have been deposited unconformably (as this is a normal fault, there is successive onlap the higher up you go) and then subjected to slips. There is some imbrication in this conglomerate — possibly reworked — and it consists of material from the unroofed Alpujárride of the Sierra Nevada — salient components are graphitic schist and mafic material (amphibolite and epidocite, a mineral associated with ophiolite complexes) (Fig. 12.1).

Figure 12.1 Conglomerate from Niguelas.

Continuing to Nerja, while some lingered over a bar lunch, others visited the Nerja conglomerate (Fig. 12.2), an important site for exploration of palaeo-environments in the Pliocene and Pleistocene. The conglomerates —poorly sorted in parts — are the product of a highly mobile complex of littoral deposits, alluvial fans and marine transgression material controlled by tectonics and eustatic climatic variations (Guerra-Merchin *et al.* 2004).

In the afternoon we examined the Torrox gneiss after turning up a road (marked ‘locals only’) into an ‘abandoned housing development’ with streetlights, pavements, roundabouts, a herd of sheep and goats and no buildings [36.755854°, –3.944324°]. This embryonic settlement sits in the dark foliated Alpujárride schist that is typical of the Costa del Sol. What we see in this exposure is a heterogeneous mix (spectacularly mineralised) of schist, mylonite, gneiss and leucogranite criss-crossed by veins (Fig. 12.3, *overleaf*). The origins of this complex have been much discussed (see Browning *et al.* 2016, 112–13).

Figure 12.2 Conglomerate at Nerja (HB).

Figure 12.3 Exposure at Torrox (RF).

A possible history may be derived, however. The precursor of the gneiss was a quite substantial Hercynian (zircon dating) crustal melt intruded into the (sedimentary) precursor of the Alpujárride schists. The banding of the gneiss and the banding of the schists is parallel, which indicates that both have been subject to the same metamorphic/deformation event — this was also Hercynian (see Abalos *et al.* 2002, 182) and pre-dates the Betic deformation.

The leucogranites may be products of localised partial melting of the gneiss — the mineralogy supports this: there are abundant tourmaline crystals (Fig. 12.4), and biotite schlieren, either the mafic residue of the melt or the product of shearing. The metamorphic mineral assemblage of kyanite, andalusite (Fig. 12. 5), and garnet with cordierite (Fig. 12. 6) suggests that the P/T trajectory of this rock has not been straightforward. It appears that the Hercynian Complex was buried, exhumed, decompressed (breakdown of garnet to cordierite) and, owing to thickening of the crust, there was melting at depth.

Conclusion

We rounded off the trip with an excellent summary by Tom over our pre-dinner drinks at the Málaga Nostrum Hotel (Fig. 12.7, *opposite*) and then during dinner had the pleasure of presenting him with two photographs of birds taken by local wildlife photographer and guide Mick Richardson. The next morning some left for the airport while those who were going back a day or two later took the opportunity to explore Málaga with visits to the Gibralfaro hill and its Alcazaba in particular. We would like to extend our thanks to Tom for a further demonstration of excellent knowledge and leadership, to Jan for her careful and thorough organisation, to the car drivers for getting us to the locations, and to all those who have contributed reports and photographs to this article.

Figure 12.4 (left) Tourmaline in leucogranite, Torrox (RF).
Figure 12.5 (centre) Andalusite at Torrox (RF).
Figure 12.6 (right) Garnet with cordierite at Torrox (RF).

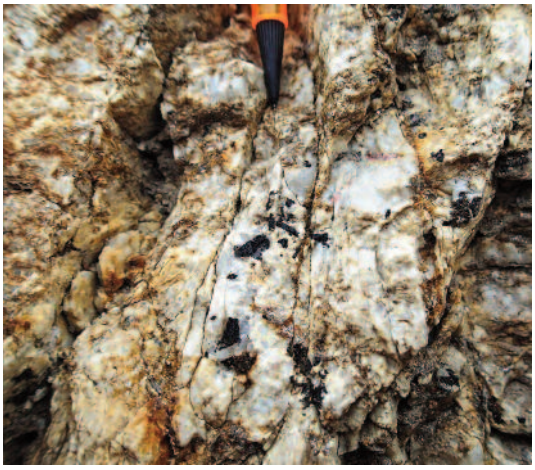


Figure 12.7 Tom summarising the trip over drinks at the Málaga Nostrum Hotel on the last evening (LF).

References

Abalos, B., Carreras, J., Druguet, E., Viruete, J. E., Pugnaire, M. T. G., Alvarez, S. L., Quesada, C., Fernandez, L. R. R., and Gil-Ibarguchi, J. I. (coordinator) 2002 'Variscan and pre-Variscan tectonics', in Gibbons, W., and Moreno, T. (eds) *The Geology of Spain*. London: The Geological Society, 155–83

Azanon, J. M., Azor, A., Booth, G., and Torcal, F. 2004 'Small-scale faulting, topographic steps and seismic ruptures in the Alhambra (Granada, South East Spain)'. *J Quatern Sci* **19**, 219–27

Browning, J., Capstick, S., Deans, C., Fowler, L., Freeman, M., Hodgson, C., Newton, T., Perkins, M., Skillerne de Bristow, B., Speak, P., Strimpel, O., and Swales, S. 2016 'Mantle in the Mountains: a geological excursion to the Betic Cordillera in Málaga and Granada Provinces, Andalucía, Spain'. *Proc OUGS* **2**, 89–114

Guerra-Merchan, A., Serrano, F., and Ramallo, D. 2004 'Geomorphic and sedimentary Plio-Pleistocene evolution of the Nerja area (northern Alborán basin, Spain)'. *Geomorphology* **60**, 89–105

Book review

Gaspar, J. L., Guest, J. E., Duncan, A., M., Barriga, F. J. A. S., and Chester, D. K. (eds) 2015 *Volcanic Geology of São Miguel Island (Azores Archipelago)*. London: The Geological Society, Geol Soc Mem 44 (ISBN 978-1-86239-731-6; hardback, 309pp; £95)

Volcanic eruptions, landslides, degassing, geothermal energy: there is plenty to capture the reader's attention in this book. São Miguel is the largest and most volcanically active of the nine islands comprising the Azores archipelago in the mid-Atlantic. In 2006 I took an OUGS group there 'cold', never having visited the island myself, but attracted by the advent of a weekly direct flight from the UK, quicker and cheaper than having to travel via Lisbon. At that time this book would have been invaluable as, although I had a lot of help from a contact at the Centre for Volcanology and Geological Risk Evaluation (CVARG) at the University of the Azores in Ponta Delgada, it would have saved me additional lengthy literature searches to find the background material that has been brought together here.

The Memoir is dedicated to John Edward Guest ((1938–2012), a geologist who made a significant contribution to Azorean volcanology, but who, sadly, died during the preparation of this book. His input is evidenced by his co-authorship of four of the 21 papers in the volume.

Following a scene-setting introduction, the book is split into five sections covering the geological setting of the islands on the Azores Triple Junction, and the volcanic history of São Miguel, its geological hazards and risk assessment, volcano monitoring and the island's natural resources. There are three active volcanoes on the island and one of them, Furnas volcano, was selected in 1993 as one of the European Union's 'Laboratory Volcanoes', which encouraged much research, especially into volcanic hazards. Consequently this volume could be of particular value to those interested in volcanic hazards, as about 40% of the Memoir concerns these.

As well as the obvious concern of eruptive frequency of the volcanoes, other hazards covered include landslides, CO_2 degassing and radon emanations. Some coastal villages have only a single route to them, which could easily be cut by eruption or landslide; many inland villages are situated within calderas and the first warning of rising CO_2 was often when small animals such as cats succumb to gas inhalation. Consequently we were fascinated, on our visit to CVARG, to be shown simple, portable gas-monitoring equipment that is used on a regular and frequent basis in these areas, as well as permanent monitoring stations. The book also describes monitoring of seismic activity, hydrogeochemical analysis of mineral waters, and GPS analysis of tectonic and volcanic deformation.

Living on a volcanic island is not all about risk though: São Miguel benefits, like Iceland, from its geothermal power and the final paper deals with the way that in recent years the Ribeira Grande geothermal field has supplied some 20% of the island's capacity to generate electricity, and outlines the potential for this to be increased in the future.

— Linda Fowler, BA Hons (Open), retired member of the Department of Environment, Earth and Ecosystems, former S260/S276 tutor, and leader of OUGS "Volcanoes on a Shoestring" trips to Tenerife, Fuerteventura, Lanzarote, and São Miguel since 1996

Book review

Hudson, John D., Miller, Angus D., and Allwright, Ann 2016 *The Geology of Eigg*. Edinburgh Geological Society (ISBN 978-0-904440-15-7; paperback, 72pp; £7)

This book accurately matches its subtitle: "a description of the geology of Eigg, for all those interested in the landscape and natural history of the Hebrides, with suggested excursions". It is very clearly written, with an attractive layout that will have a wide appeal, but provides sufficient detail to be useful to the serious geologist. It is also a pleasure to read, as it links to the rich history of geological investigation on Eigg by quoting passages from the writings of Hugh Miller and Archibald Geikie.

The pitchstone ridge known as the Sgurr of Eigg dominates the landscape and has also been prominent in the geological literature on Eigg. The book reviews the controversies that developed over the origin of the Sgurr, from Geikie's prescient ideas of an acid lava flow filling a pre-existing river channel, through Harker's reinterpretation as a sill, to Brown and Bell's assertion in 2013 that the Sgurr is a lava-like ignimbrite. A suggested excursion around the Sgurr gives detailed guidance on where critical evidence may be examined in the field. This excursion is one of seven that enable exploration of the geology of the whole island, which has a sequence of Jurassic sediments as well as dykes, sills and lava flows. The routes of all excursions are shown on a series of sketch maps, but grid references are also given, so excursions can also be followed on OS maps.

This book is produced in a clear font and is well illustrated with both photographs and line drawings. It includes a glossary of the geological terms used and an up-to-date list of further reading. The book is strongly bound and thus should survive the rigours of use in the field. It reminds me that my visit to Eigg is long overdue!

— Duncan Woodcock, BSc Hons (Open), PhD, and continuing ES student

More Mantle in the Mountains: petrographic report

Julian Overnell

Introduction

This report comprises interpretations of thin sections I made of rocks collected on the trip at several of the locations visited. (The locations and their geological settings are described in the preceding field report).

Measuring a specimen's specific gravity (SG) is quick, cheap and gives additional information about it (sometimes only available by chemical analysis). Quartz and alkali feldspars have SGs of ~2.6; thus, also for granites and many sedimentary rocks. Basic rocks have higher values. Ultra basics and high-pressure rocks have SGs greater than 3. Highly hydrated rocks — e.g. serpentinites — and glasses have lower values, ~2.4.

Methods

A few samples were removed from bedrock, but most samples were loose in context, for example, in recent road cuts where the debris had clearly come from the adjacent face. However, we also visited stream beaches and stream sections with many interesting cobbles. These were clearly not in context and must have come from upstream.

Map references of sampling locations are UTM co-ordinates. All were in rectangle 30S. (Spanish 1:50,000 maps are plotted on a UTM grid). In order to relate these locations to those in the main report I have also given their WGS84 co-ordinates immediately after the UTM co-ordinates.

Specific gravities were recorded by weighing the hand specimens in air and again in water, using a small strain-gauge weighing machine (0.0–1.0kg × 0.1g). A thread was attached to the pan side of the strain sensor, and the thread fed out of a hole cut in the bottom so that samples could be hung underneath. Errors due to weighing inaccuracies were small.

Sample blocks were glued to microscope slides using high temperature epoxy resin 'Petropoxy', sawn off and thinned by hand to ~35µ (30µ + a nominal 5µ for the glue thickness). I made 29 thin sections, but only a subset is described here.

I took photomicrographs with an iPad above the vertical eyepiece of a trinocular polarising microscope, using ×2.5, ×4 or ×10 objectives.

Descriptions of locations, samples and thin sections

Thursday 21 April

Location: Col, roadside exposure, northern Estepona, S Spain (UTM 30S 303950, 4042155; WGS84 36.504672°, –5.189126°).

Outcrop of brown rock, much fractured, sample 21/04/16_1, SG = 2.99, suggesting a basic or ultra-basic rock with little quartz or alkali feldspar (illustrative portions shown in Figs. 1 and 2).

The mineral with many random, pale brown altered fracture lines and 2nd-order birefringence is forsterite olivine. The isotropic pink anhedral mineral in the centre is assumed to be a spinel. The large low birefringence mineral above is orthopyroxene and the squarish mineral with blue birefringence to the lower left of the spinel is clinopyroxene. The pink/strong pink spinels in these rocks are invariable ragged and anhedral, and appear similar in form whether the rock is fresh or altered; the spinels are apparently unaffected by the process that produces serpentinisation of the olivines. A suggested rock name is: spinel-bearing lherzolite; peridotite.

Location: Outwash fan of river by culvert bridge at Refugio, northern Estepona, S Spain (UTM 301862, 4045107; 36.530835°, –5.213182°).

Figure 1 PPL ×4, FoV* 4.6mm.*

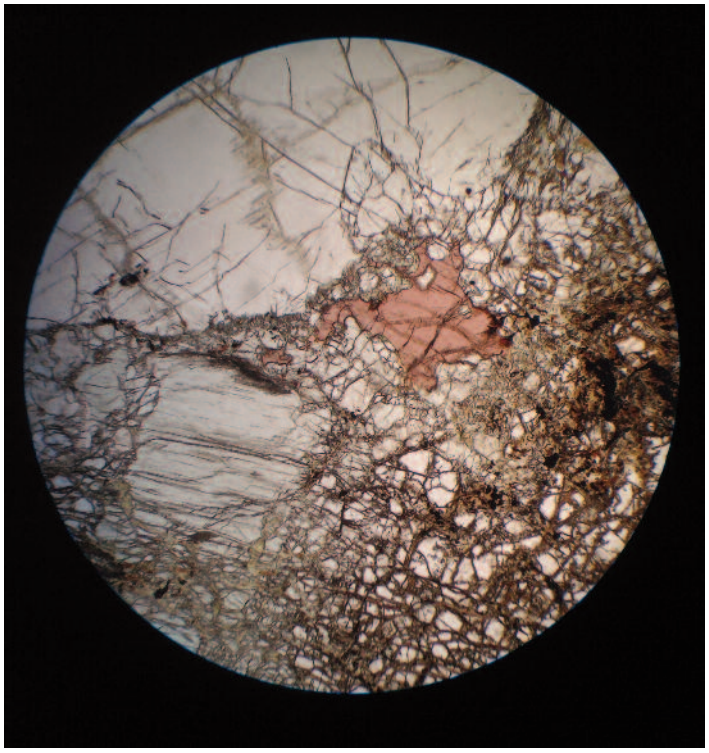
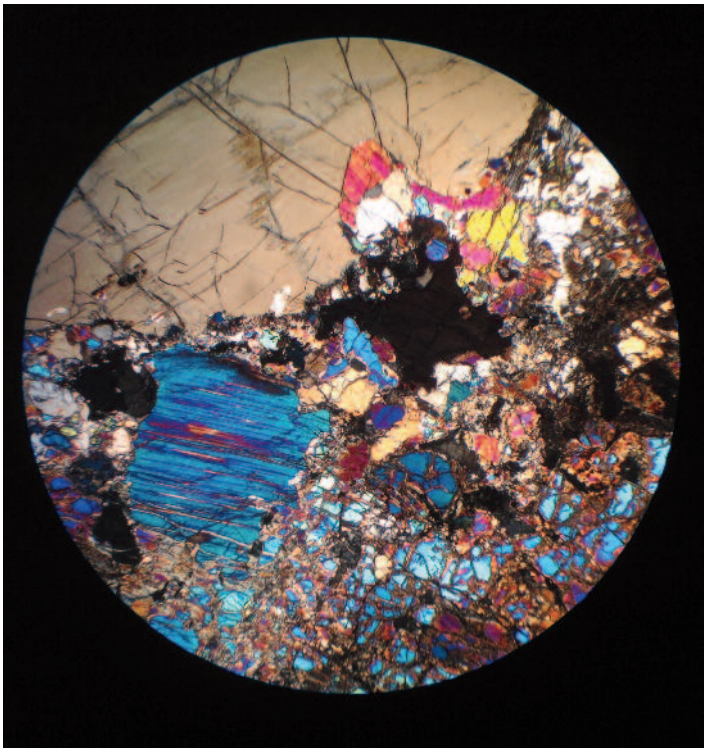


Figure 2 XPL ×4, FoV 4.6mm.*



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Several cobbles were recovered here, including two with SGs of ~3.0, both similar to sample 21/04/16_1 (*see above*), and one with SG = 2.48. This latter was a much-altered peridotite, now mostly serpentinite, with a few small relict fragments of pyroxene and/or olivine. There is also banded quartzo-feldspathic gneiss with foxy brown biotite in dark layers; also a grey, high-grade metamorphic rock with beautiful pale purple garnets — such garnets were not uncommon in the cobbles at this location, *see* sample 21/04/16_5 SG = 2.99, Figures 3 and 4.

In Figure 5 the blocky elongate mineral in the centre with top 1st-order blue birefringence in XPL is sillimanite. On its lower left is a garnet set in corona of ?feldspar. On the right of the sillimanite is an area of probable cordierite enclosing many dark grey isotropic grains of spinel. The sillimanite also encloses a small round zircon in its left-hand side, although this is difficult to spot in the image.

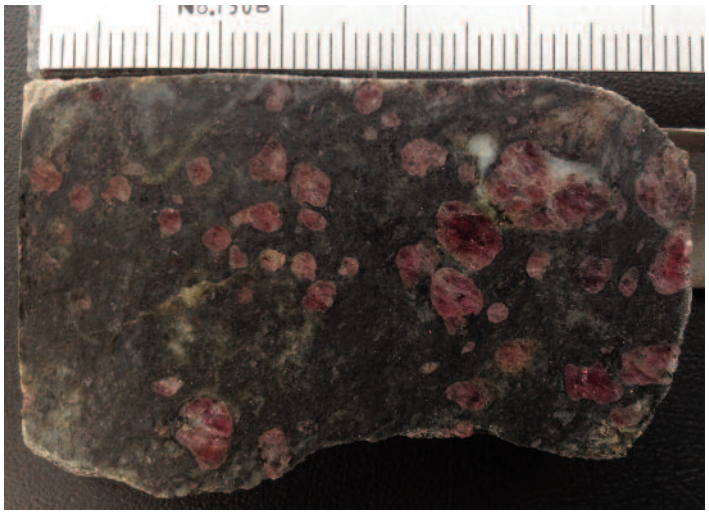
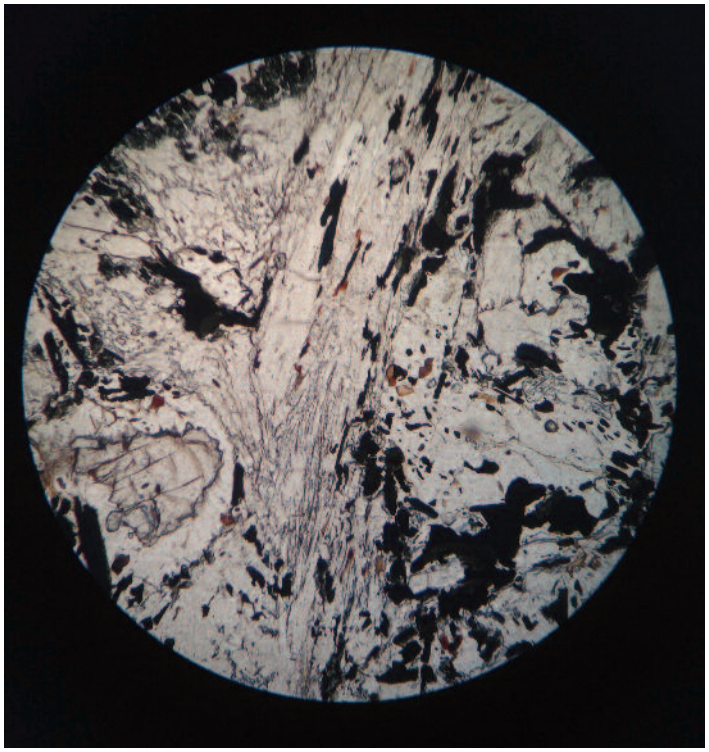


Figure 3 Sawn slice of a kinzigite cobble, with purple garnets, length 55mm. Thin sections of this sample are shown in Figs 4 and 5.

Figure 4 PPL ×10, FoV 1.85mm.



This specimen is a quartz-garnet-sillimanite-cordierite+alteration product-spinel-biotite metamorphic rock with trace zircon, i.e. kinzigite. (Cordierite can be rather difficult to identify unambiguously in thin section, when, as in this sample, it contains neither characteristic yellow to colourless pleochroic halos nor characteristic twinning.) Tom Argles told us that, "Kinzigite certainly exists upstream from the lunch stop; that river has quite extensive headwaters across the peridotite-gneiss boundary". Another example of this rock type was seen later on 26 April.

Note: Kinzigite was originally defined as "a high grade metamorphic rock, mainly composed of pyrope garnet, biotite and plagioclase, smaller amounts of quartz, and graphite, with as accessories, zircon, ore minerals and sericite pseudomorphs after cordierite. Now used for a garnet-sillimanite-cordierite gneiss." (Fettes and Desmons 2007).

Location: Lookout point below summit of Pico Reales, northern Estepona, S Spain (UTM 302801, 4039080; 36.476735°, –5.201163°).

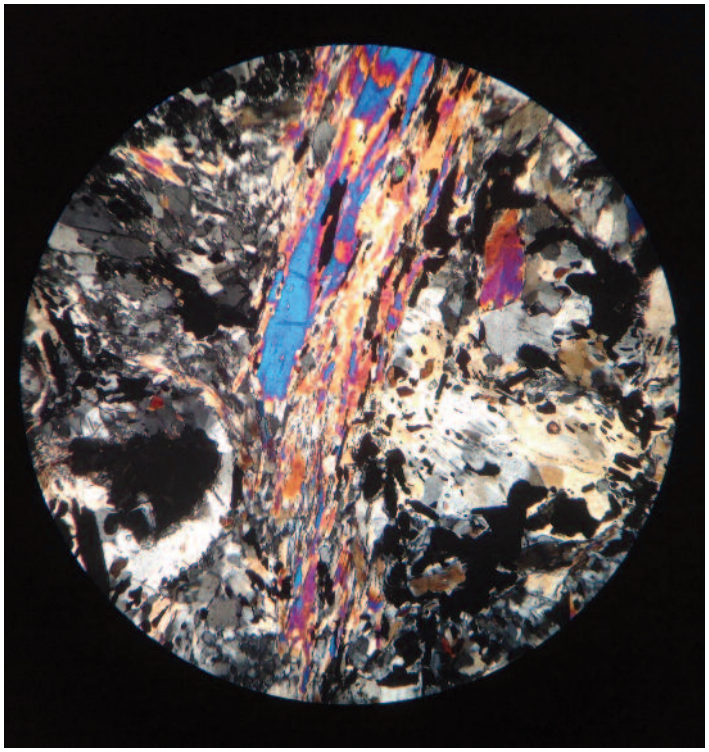
Pale brown loose pebble, in context. Sample 21/04/16_7, SG = 2.36; another sample had a SG of only 2.14, suggesting altered, hydrated rocks.

In thin section Sample 21/04/16_7 is an most completely altered rock of mostly clear serpentinite and pale brown ?iddingsite, but with relict pyroxene within the brown alteration product, and minor unaltered anhedral strong pink spinel. Altered hydrated peridotite.

Location: Roadside stop at bridge, northern Estepona, S Spain, (UTM 0304625, 4039262; 36.478748°, –5.180862°). Stream bed with exotic heavy cobbles among boulders.

Cobble sample 21/04/16_9, SG = 3.25, suggesting an ultrabasic rock. This was an olivine websterite, fairly fresh, comprising forsterite, clinopyroxene and orthopyroxene, and with minor pink/brown spinel. The clinopyroxenes have interesting 'barbed wire' ex-solution lamellae (Fig. 6, *opposite*).

Figure 5 XPL ×10, FoV 1.85mm.



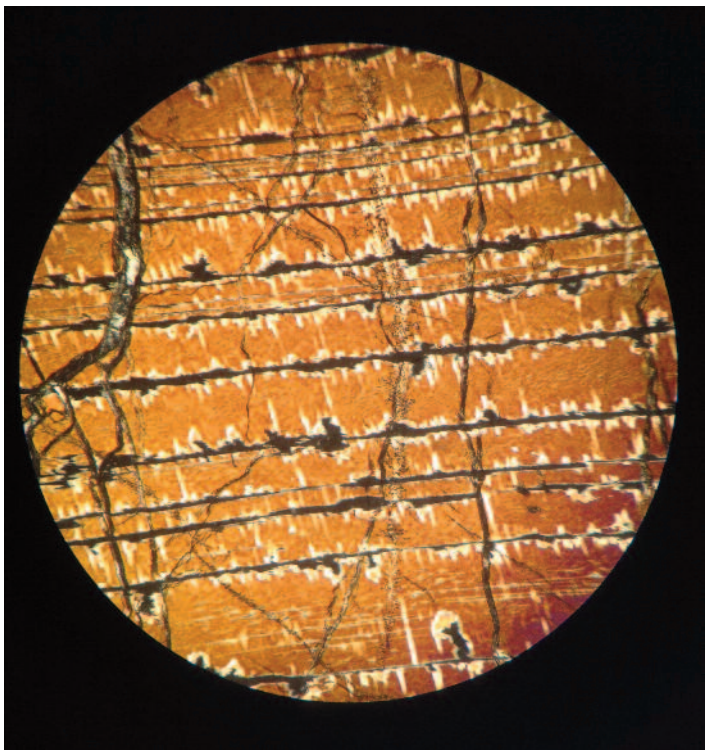
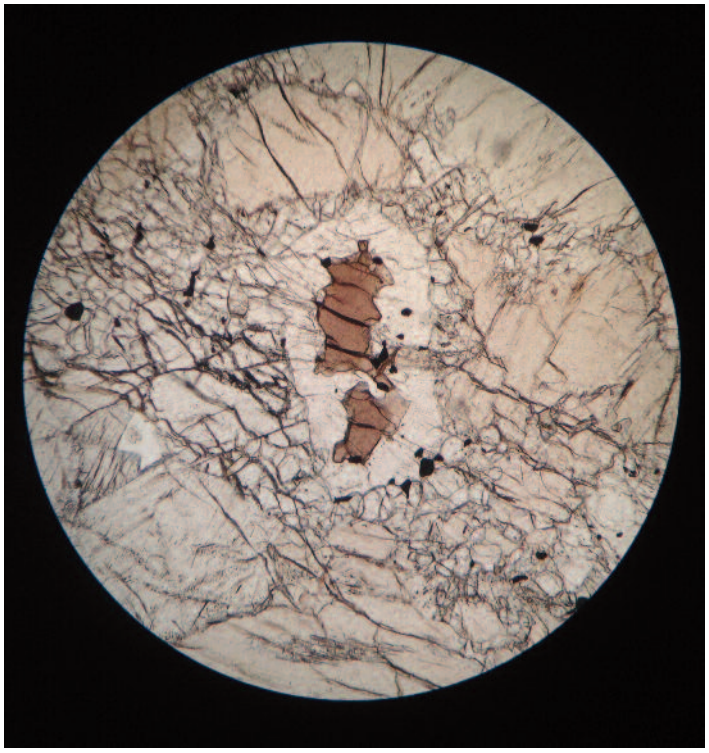


Figure 6 XPL ×10 FoV 1.85mm.

This 'barbed wire' effect is probably due to initial ex-solution of orthopyroxene forming the 'wire', followed later in the cooling by ex-solution of another orthopyroxene phase along a different crystallographic axis, forming the 'barbs'; for a description of this effect see: http://www3.imperial.ac.uk/portal/pls/portallive/docs/1/2285912.PDF.

Sample 21/04/16_9 also shows a ragged anhedral pink/brown spinel surrounded by a corona of small-grained plagioclase (Figs 7 and 8).

Figure 7 PPL ×10 FoV 1.85mm.



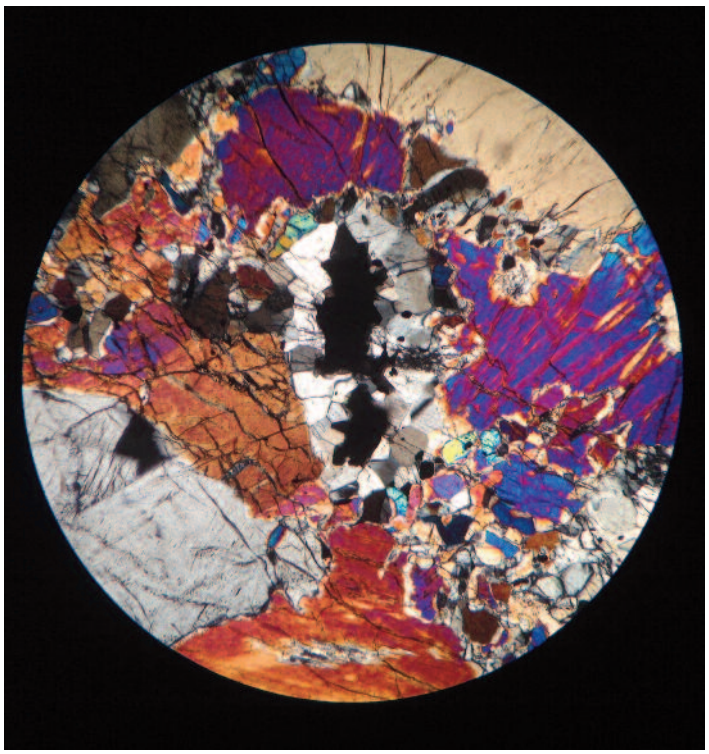


Figure 8 XPL ×10 FoV 1.85mm.

Sample 21/04/16_10 is from the same location. It is another peridotite rock, SG = 3.15), but in this case it contained minor anhedral green spinel (not illustrated).

Saturday 23 April

Location: River beach lunch stop in park, road from Genalgaucil to Jubrique, S Spain (UTM 298972, 4049179; 36.566913°, –5.246503°).

Loose flat pebble on river beach, Sample 23/04/16_1. This is a grey schist with a silky lustre, and with elongate black upstanding 'minerals' (Fig. 9); not in context.

Figure 9 Silky beach pebble.

In thin section Sample 23/04/16_1 is a dark, highly graphitic sericite schist with thin veins of biotite and porphyroblasts, comprising garnet in the centre, surrounded by fine-grained white mica (biaxial -ve 2V ~20°). There are no obvious minerals corresponding to the black, upstanding structures.

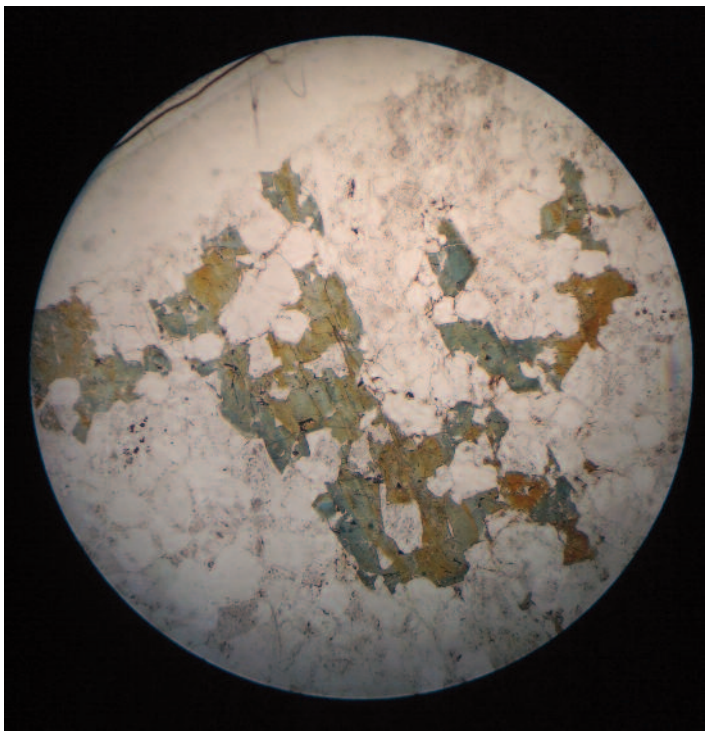


Figure 10 PPL ×2.5 FoV 7m — dusty feldspar and quartz, with pale brown and pale blue schorl tourmaline.

Tuesday 26 April

Location: Peak (726m) in Sierra de las Aguas, S Spain (UTM 339973, 4080707; 36.858748°, –4.795141°).

Outcrop of pale brown rock with ragged black minerals; Sample 26/04/16_1, loose in context, SG = 2.51. The thin section is illustrated in Figure 10.

Sample 26/04/16_1 comprises feldspar and quartz, and the ragged black minerals in hand specimens are pleochroic from brown and blue to nearly colourless, (uniaxial –ve.), schorl tourmaline. The SG is typical of a granite. This is a leucogranite melt rock with schorl tourmaline.

Location: Road cut on A357, inspected where it passed through the Cerro Tajo fault at UTM 340488, 4076404; 36.820063°, –4.788463°.

The rock examined from here is green, and is from the rock fall of the 45° fault — Sample 26/04/16_3, SG = 2.69. In thin section it shows a partially serpentinised peridotite with relict forsterite and pyroxene, and minor red/strong pink isotropic spinel.

Location: Parking spot for stop above UTM 339843, 4076591; 36.821639°, –4.795731°.

Apparently local boulders of grey/brown crystalline rock — Sample 26/04/16_4, SG = 2.64. This was a lithified ash containing angular crystal grains of quartz, feldspar and minor garnet with lithic clasts of crystalline rocks mostly comprising quartz, feldspar, garnet and biotite, in a fine-grained matrix of quartz, feldspar, bent biotite flakes, and brown unidentifiable material (Figs 11 and 12).

Location: Track just E of Carratraca, on road to Alora (UTM 338392, 4080188; 36.853802°, –4.812758°).

Loose clast in track at approximate position where the track crossed the outcrop mapped as kinzigite — Sample 26/04/16_2, SG = 2.87 (collected by R. Fraser).

Sample 26/04/16_2 is a foliated metamorphic rock with quartz, dusty feldspar, very fine-grained 'sericite' and containing flakes of ?graphite, garnet and bundles of sillimanite. The sericite is probably an alteration product of original cordierite (none of which was seen in thin sections of this sample). This composition is consistent with kinzigite, a bit altered in this example.

Saturday 30 April

Location: Road stops on way to Sierra Nevada ski area. Metamorphic rocks. I examined seven loose pieces in recent road cuts, all in context. These are highly strained rocks with a strong fabric.

Sample 30/04/16_1 (UTM 461738, 4107329; 37.111506° –3.430654°), SG = 2.60. This is an arkose with

Figure 11 PPL ×4 FoV 4.6mm

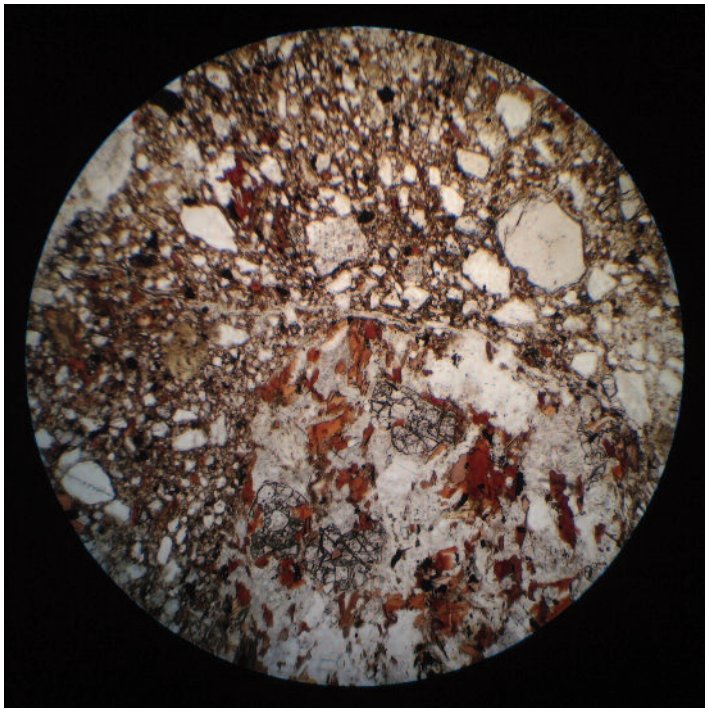


Figure 12 XPL ×4 FoV 4.6mm

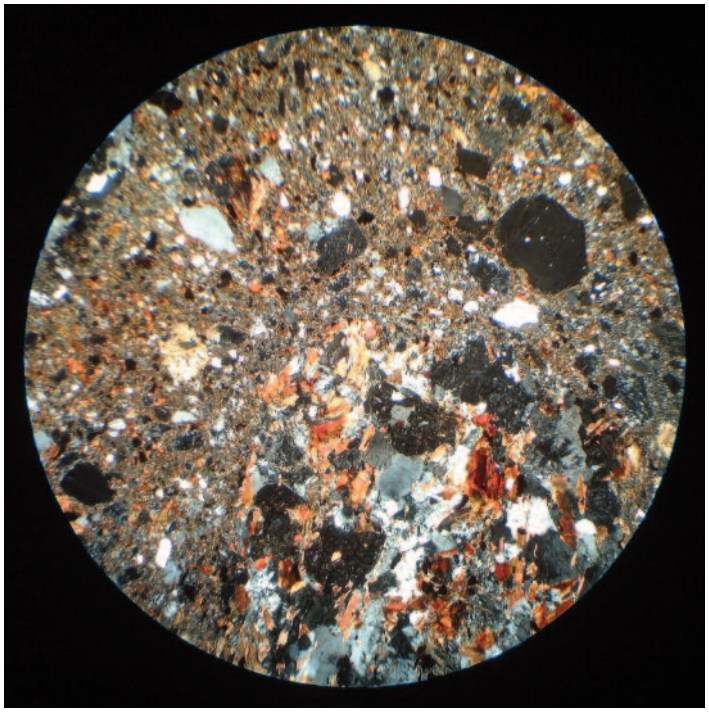


Figure 13 PPL ×4 Field of view 4.6mm.

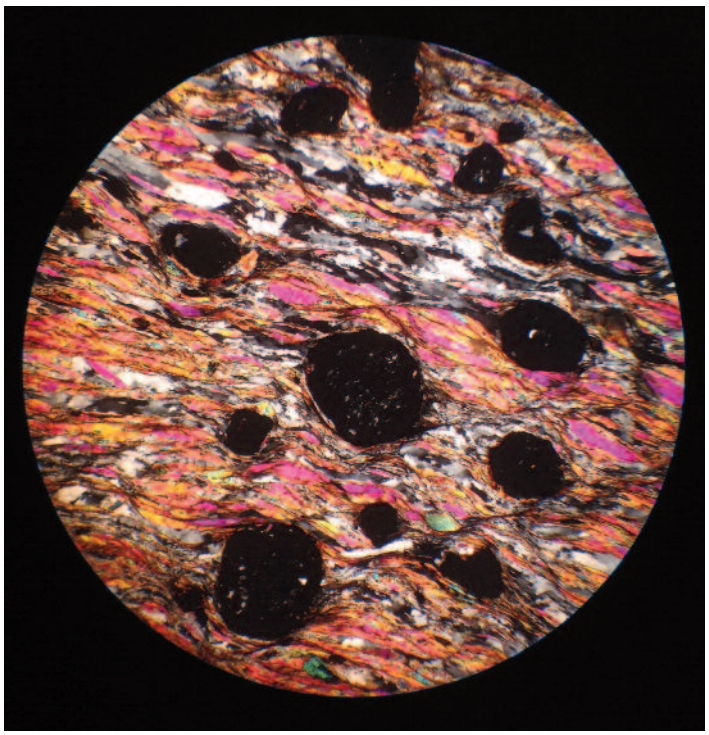


Figure 14 XPL ×4 Field of view 4.6mm.

recrystallised quartz and whisps of white mica, and containing shattered pieces of highly pleochroic schorl tourmaline (uniaxial –ve). Its SG is consistent with a quartz-feldspar rock.

Sample 30/04/16_5, (UTM 463233, 4107267; 37.111007°, –3.413825°), SG = 2.84.

A white mica-quartz-garnet schist with abundant round garnets and a trace of possible rutile (Figs 13 and 14). The SG is consistent with a rock rich in muscovite (~2.8) also containing quartz and garnet.

In Figures 13 and 14 the white mica has been slightly altered and stained brown/orange, which shows up the foliation well. The foliation is seen to wrap round the garnets, possibly after their main phase of growth.

Sample 30/04/16_4 (UTM 463233, 4107267; 37.111007°, –3.413825°), SG = 2.86.

This is a graphitic white mica schist with porphyroblasts of pink garnet, and with quartz in the strain shadows. One garnet shows traces of dark inclusions in the form of a tight fold (Fig. 15).

Note the lithic clast in the bottom right quadrant of Figures 11 and 12: rich in foxy brown biotite and containing garnets with fracture lines. Above and left of this clast is a crystal-rich ash with larger angular fragments of garnet without fracture lines.

Sample 30/04/16_4 shows a garnet in white mica schist. Its folded pattern of dark inclusions suggests that the garnet grew over and incorporated dark inclusions from an already tightly folded region of the schist, which was further sheared by active syn tectonic growth.

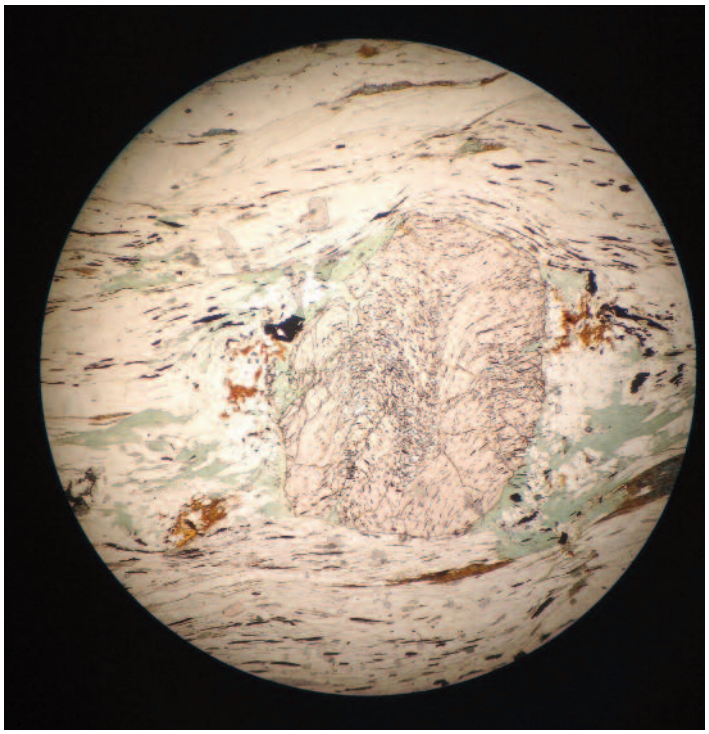
Sunday 1 May

Location: We examined the Torrox gneiss at the site of an unfinished and apparently abandoned housing development (UTM 415912, 4068246; 36.756244°, –3.942052°).

The gneiss was brown and folded. I collected three samples of SG = 2.60, 2.61 and 2.65, all loose in context, from leucocratic veins within the brown gneiss. They were selected because they contained dark minerals. The vein rock is a quartz-dusty feldspar-white mica rock with isolated dark minerals (schorl tourmaline) and in one sample a 10mm garnet crystal. This crystal had many fractures filled with a dark alteration product. Figure 16 *(overleaf)* shows a leucocratic vein *in situ* containing dark euhedral minerals.

This rock is therefore a broad leucocratic vein within Torrox gneiss, showing euhedral dark minerals of probable schorl tourmaline.

Figure 15 PPL ×2.5 FoV 7mm.



Conclusion

The rocks found on this trip are peridotites showing varying degrees of alteration, highly strained metamorphic garnet schists, granitic melt rocks with schorl tourmaline and an unusual high grade metamorphic garnet-sillimanite-cordierite-biotite-spinel rock called kinzigite. The peridotite samples all contained minor pink/red spinel. One mineral not seen these samples is andalusite.

Reference

Fettes, D., and Desmons, J. (eds) 2007 Metamorphic Rocks: A Classification and Glossary of Terms. Cambridge UP

Fiure. 16 Leucocratic vein (in situ) *with dark euhedral minerals.*

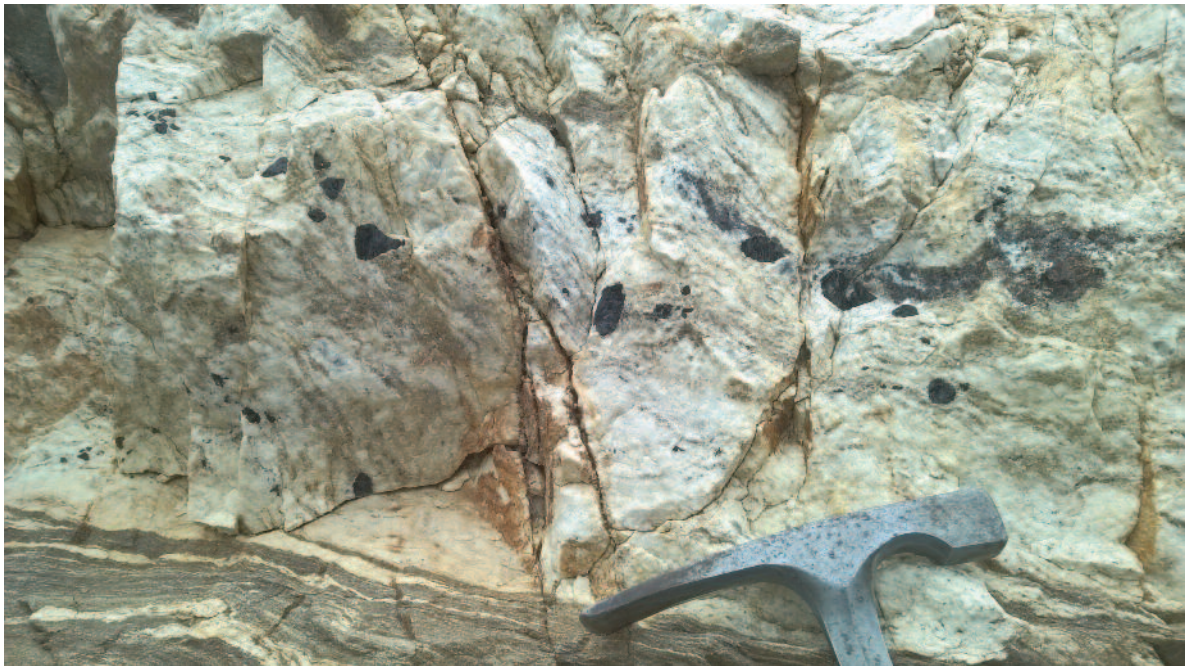


Table 1 Stratigraphy of the Sorbas Basin. Dates in Ma from Walker *et al.* (2012)

Period	*Epoch*	*Stage Date (Ma)*	*Formation*	*Member*	*sediments deposited*	*dDepositional environment*	*notes*
Quarter-nary	Holocene / Pleistocene	2.6			river terrace gravels alluvial fans	terrestrial — continued uplift, so mainly erosional	
Neogene	Pliocene		Gochar		coarse conglomerates	terrestrial — braided rivers and alluvial fans	
			Cariatiz	Moras	alluvial fan conglomerates	basin margins	time equivalents
		5.3		Zorreras	fluvial sands, silts and clays	coastal plains	
	Miocene	Messinian	Caños	Sorbas	aeolian shallow marine	prograding beach-barrier in normal salinity	shallowing upwards
				Yesares	gypsum intercalated with marls	cycles of dessication and recharge	unconformity at base
			unconformity				
			Turre	Cantera	reef limestones (tropical)	basin margins	time equivalents
				Abad	marls	basin	
		7.2		Azagabor	temperate carbonates	shallow marine, normal salinity	unconformity at base
		unconformity					
		Tortonian 11.6	Chozas		turbidites	submarine fans, marine with moderate depth	sourced from Sierra de los Filabres
		Serravallian 13.8			conglomerates and sands		unconformity at base
unconformity							
Mesozoic Paleozoic	Metamorphic basement of Paleozoic and Mesozoic sedimentary and igneous rocks deformed and metamorphosed during the Tertiary, producing the Betic Cordillera nappes.						

Miocene-Pliocene sedimentation in the Sorbas Basin, Almería region, south-east Spain and its relationship to the Messinian Salinity Crisis

Dr Duncan Woodcock

Abstract

The Sorbas Basin contains an overall shallowing-upward sequence of Miocene–Pliocene marine and terrestrial sediments that is punctuated by the Yesares Member, which comprises up to 160m of gypsum-marl cyclic sedimentation. The development of the basin was controlled principally by regional tectonics associated with plate convergence and, in particular, by the Messinian Salinity Crisis and its aftermath. The Yesares gypsum is a dominant control on landform in the Sorbas area; a field guide to these distinctive rocks in the Los Molinos area is presented.

1. Introduction

1.1 Regional geology

During the late Mesozoic the southern margin of the Iberian peninsula was subjected to compression resulting from the convergence of the European and African plates. Compression continued through most of the Tertiary resulting in northward thrusting of Paleozoic and Mesozoic rocks to produce a stack of thrusts that became the Betic Cordillera (Mather *et al.* 2001).

Compression was replaced by left-lateral transtension in the mid Neogene. This enabled the development of sedimentary basins between uplifted blocks of the metamorphosed Betic basement. The accommodation space produced was progressively filled by an overall shallowing-upwards sequence of marine to terrestrial sediments (Mather *et al.* 2001).

Figure 1 shows the main sedimentary basins of the Almería region, together with the uplifted basement blocks or 'sierras'. The Sorbas Basin contains the most complete sedimentary succession, which is well exposed by a combination of erosion and a semi-arid climate (Harvey and Mather 2015).

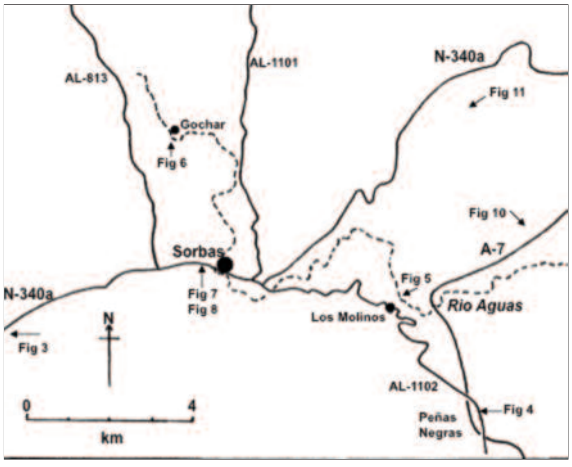
1.2 Sorbas Basin sedimentation and stratigraphy

Table 1 *(previous page)* summarises the stratigraphy of the Sorbas Basin. Figures 3–8 *(on following pages)* comprise a set of photographs that show some of the sediments. Figure 2 shows the location of the outcrops in the photographs, together with the main roads and locations mentioned in the text.

Mid-Miocene (Serravallian) conglomerates, sourced by erosion of the Sierra de los Filabres, were deposited in the developing basin. In the Tortonian the basin rapidly deepened, enabling normal marine conditions to become established with the deposition of turbidites. Towards the end of the Tortonian a temporary return to a compressional regime folded and uplifted the turbidites (Harvey and Mather 2015). During the early Messinian shallow marine conditions with normal salinity prevailed in which temperate carbonates were deposited on the eroded late Tortonian surface, followed by tropical carbonates as the climate warmed (Mather *et al.* 2001).

Figure 1 The principal sedimentary basins and uplifted basement blocks (sierras) of the Almería region. The black square on the inset map shows the location of the Almería region on the Iberian peninsula.

Figure 2 Sketch map of the Sorbas Basin, showing the locations of Figures 3–8, together with main roads (solid lines) and Río Aguas (dashed line).



The mid-Messinian sequence in the Sorbas Basin is marked by a major unconformity due to erosion following a marine regression (Riding *et al.* 2000). A cyclic sequence of gypsum and marls, with maximum thickness of 130m, was deposited above the unconformity. Shallow marine conditions with normal salinity became re-established in the late Messinian with the deposition of a prograding beach-barrier deposit. During the Pliocene, the shallowing-upward trend continued, when coastal and fluvial sediments were overlain by alluvial fan conglomerates (Mather *et al*. 2001).

The mid-Messinian unconformity, together with the overlying gypsum and marl beds, represents a hiatus in the overall shallowing-upwards sequence of the Sorbas Basin. The origin of this hiatus was not well understood until the 1970s, when a programme of deep sea drilling took place in the Mediterranean.

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Figure 3 Serravallian conglomerates, Rambla Sierra, Tabernas, 37° 02.493' N 02° 23.953' W. Note the discoidal clasts eroded from schists of the Sierra de los Filabres (hammer = 280mm long).

1.3 The 'Messinian Salinity Crisis'

Before the 1970s, sedimentary sequences containing evaporites of Messinian age were known to occur at Messina, Sicily, on Crete and Cyprus, and in south-eastern Spain, but were considered to be local deposits (Hsü 1983). In addition, a seismic survey of the Mediterranean carried out in the 1960s had delineated a prominent reflector, the 'M' reflector, that was up to 2km thick and showed diapirism into the overlying sediments, similar to salt domes in other locations (Hsü 1987). This inferred evaporite deposit was considered by many to be Triassic in age (Hsü 1983).

The research drilling ship *Glomar Challenger* visited a number of sites in the Mediterranean during Leg 13 of the Deep Sea Drilling Project in 1970, when the 'M' reflector was shown to be an evaporite, with both anhydride and halite recovered in cores. More unexpected was the nature of the sediments between individual evaporite layers: these contained stromatolites together with nodular anhydride showing a 'chicken wire' texture characteristic of evaporation in a shallow environment (Hsü *et al.* 1973; Kendall 1984). In addition, the sediments both above and below the evaporite layer were found to have been deposited in a deep marine environment of normal salinity (Hsü *et al.* 1977).

By the end of Leg 13, a consensus model had emerged that suggested evaporite deposition from shallow water within a deep basin. The implication that the Mediterranean had dried out during the Messinian was greeted with disbelief in some quarters (Hsü 1983); however, additional corroborative evidence for this 'Messinian Salinity Crisis' was soon forthcoming.

During the 1960s, Soviet geoscientists had carried out a seismic survey across the Nile at Aswan, some 1200km upstream of the Nile delta, in preparation for the design and construction of the Aswan Dam. The results of the survey were unexpected: below the river sediments the Nile had eroded a channel in the underlying bedrock granite that extended down to 200m below present sea level (Hsü 1987). This observation lent support to the idea that the Mediterranean sea level was once much lower than at present.

Figure 4 Tortonian turbidites, Peñas Negras, 37° 03.673' N 02° 03.045' W. The prominent lower bed is c. *0.5m thick.*

Figure 5 Yesares gypsum overlying Abad marls, Río Aguas Valley at Los Molinos, 37° 05.396' N 02° 04.491' W. The marls erode much more easily than the gypsum, which is undermined and collapses.

Evaporation to dryness of the current contents of the Mediterranean would deposit a 40m thick evaporite layer over the whole basin, which, if remobilised towards the basin centre, might result in a thickness of *c.* 100m (Hsü *et al.* 1973). Thus to deposit the observed 1–2km thickness of the 'M' reflector the Mediterranean must have dried out and refilled many times. Based on the present-day Mediterranean water balance, Hsü *et al.* (1973) showed that the Mediterranean could dry out in *c.* 1,000 years. In practice the desiccation time may have been even shorter: as sea level was lowered, sea surface air temperatures would have increased at 10 °C/km (the dry adiabatic lapse rate). Air temperatures could thus have exceeded 50°C in the deepest parts of the basin. This high temperature accounts for the deposition of calcium sulphate as anhydride rather than the hydrated form gypsum (Hsü *et al.* 1977).

It is convenient at this point to summarise the main events of the Messinian Salinity Crisis in the Mediterranean basin. During the mid- to late Mesozoic, Europe and Africa were separated by an arm of the Tethyan Ocean (Hsü *et al.* 1977). In the early Miocene, the ocean became closed at the east end but retained a link to the Atlantic at the west end through the Betic-Rif Straits. By Messinian times, closure began in the west, driven by ongoing convergence of Africa with Europe together with the expansion of the Antarctic ice cap, which lowered global sea level (Hsü *et al.* 1977; Krijgsman *et al.* 1999). Intermittent isolation of the Mediterranean basin from the Atlantic enabled cycles of rapid drawdown and evaporite deposition followed by recharge. These cycles may have been orbitally forced via the waxing and waning of the Antarctic ice cap (Krijgsman *et al.* 2001). Eventually the Mediterranean refilled for the last time, enabling the re-establishment of the normal marine conditions experienced today.

2. The effect of the Messinian Salinity Crisis on the development of the Sorbas Basin

There is little doubt that the mid-Miocene unconformity at the top of the Turre Formation in the Sorbas Basin was produced by the major marine regression associated with the drawdown of the Mediterranean during the Messinian Salinity Crisis (Riding *et al.* 2000). A similar unconformity is present in the adjacent Vera Basin, indicating that both basins had no direct connection to the Atlantic, but were only indirectly connected via the Mediterranean (Riding *et al*. 1998).

In contrast to the Sorbas Basin, the Vera Basin has no evaporite sequence. Riding *et al.* (1998) suggest that this is because the Vera Basin was connected to the Mediterranean without restriction, and was thus unable to retain seawater for evaporation. Riding *et al.* (1998) suggest that the connection of the Sorbas Basin to the Mediterranean was restricted by the development of a barrier. The Sorbas Basin thus operated as a barred basin that

Figure 6 Stromatolites in Cantera limestones, Rambla de Gochar, 37° 08.455' N 02° 08.981' W (coin = 20mm diameter).

could retain any seawater entering the basin by overtopping the bar. A subsequent sea level fall thus isolated a body of seawater in the basin where it evaporated. Calcium sulphate was deposited in the relatively shallow Sorbas Basin as gypsum, rather than anhydride as in the Mediterranean basin deposits.

The timing of deposition of the Yesares gypsum-marl sequence in the Sorbas Basin relative to the Messinian Salinity Crisis has been controversial. Essentially there are two end-member scenarios

Figure 8 Gochar Formation conglomerates, Río Aguas near Sorbas, 37° 05.978' N 02° 08.238' W (hammer = 280mm long).

Figure 7 Cross-bedded sandstones deposited in the shoreface environment of a prograding beach of the Sorbas Member, Río Aguas near Sorbas, 37° 06.005' N 02° 08.077' W (hammer = 280mm long).

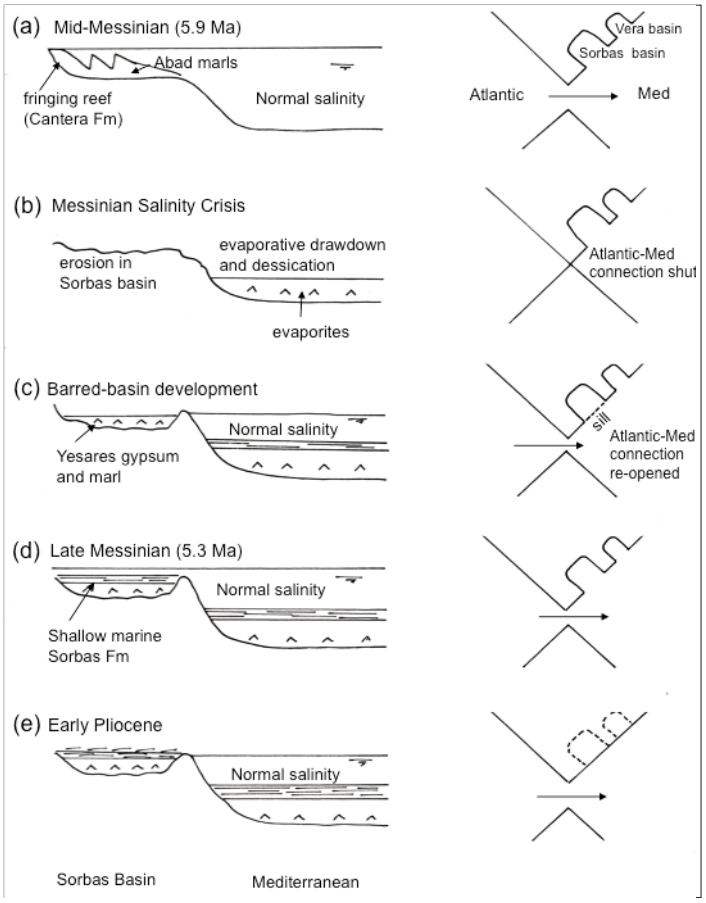


Figure 9 Model of events in the Sorbas Basin before, during and after the Messinian Salinity Crisis. The LHS set of diagrams show, in a notional NW–SE cross section, the development of the Sorbas Basin fill (cf Table 1) and deposition within the main Mediterranean basin. The corresponding RHS set of diagrams show, in schematic plan view, the connections between the Mediterranean and the Atlantic, together with those between the Mediterranean and the Sorbas and Vera basins. Within the Sorbas Basin the key events are: (a) deposition of Cantera limestones and Abad marls, (b) erosion during the Messinian Salinity Crisis, (c) cyclic filling, evaporative drawdown and gypsum precipitation controlled by a sill together with eustatic sea level variation, (d) ongoing sea level rise with deposition of the shallow marine Sorbas Member, and (e) re-emergence with terrestrial sedimentation driven by regional uplift.

(Riding *et al.* 1998): the Yesares sequence is either synchronous with or post-dates evaporite deposition in the Mediterranean basin. Synchronous deposition implies that the Mediterranean refilled to the level where the Sorbas 'bar' was overtopped in each cycle. Riding *et al.* (2000) favour the alternative where the Yesares cycles were produced after the Mediterranean was refilled for the last time and that cyclic drawdown and recharge were controlled by sea level modulation, through orbital forcing (Krijgsman *et al.* 2001). The current view is that the latter scenario is more likely to be correct (Braga *et al.* 2006).

Figure 9 is developed assuming a model from Riding *et al.* (2000) that provides a good explanation of the Messinian and early Pliocene stratigraphy in the Sorbas Basin. The key events are:

(a) Deposition of the Cantera fringing reef on the basin margins with Abad marls deposited in deeper water during a period of normal salinity when the Mediterranean was connected to the Atlantic.

(b) Closure of the connection between the Mediterranean and the Atlantic leading to repeated evaporative drawdown and desiccation during the Messinian Salinity Crisis. During this time the Sorbas Basin was emergent and subjected to erosion.

(c) Connection between the Mediterranean and the Atlantic was permanently re-established at the end of the Messinian Salinty Crisis but access of seawater into the Sorbas Basin was restricted by a sill. The Sorbas Basin thus experienced cycles of filling and evaporative drawdown with deposition of the Yesares gypsum and marl sequence. In contrast, access of seawater into the Vera Basin was unrestricted.

(d) Further sea level rise fully restored normal marine conditions to the Sorbas Basin, enabling the deposition of the shallow marine Sorbas Member, which shallows upwards due to regional uplift.

(e) Continued regional uplift caused the Sorbas Basin to be emergent with the deposition of the coastal plain and fluvial Cariatiz Formation.

3. Field guide to the Yesares gypsum of the Los Molinos area

The Yesares gypsum-marl deposits are the most distinctive units in the Sorbas Basin. The gypsum is relatively resistant to erosion in the semi-arid climate so it forms escarpments that dominate the topography (*see* Fig. 5). Where the gypsum is exposed at the surface, the limited precipitation has developed a karstified surface (Fig. 10), but the extensive development of surface karst features, such as those developed on limestones in humid regions, is absent. Exploitation of the gypsum deposits provides major

Figure 10 Karstified gypsum surface — southern edge of gypsum plateau overlooking La Herreria, 37° 06.668' N 02° 02.285' W (hammer = 280mm long).

Figure 11 Opencast gypsum mine on gypsum plateau, c. *7km north-east of Sorbas (photo taken through convenient gap in security fence at 37° 07.495' N 02° 03.124' W).*

economic benefit to the region: the Sorbas opencast mine (Fig. 11) is the largest in Europe with a production exceeding 1.5Mte/yr (Lunar and Moreno 2002).

The Yesares gypsum-marl sequence attains its maximum thickness of 130m in the centre of the Sorbas Basin immediately east of Sorbas town. Most field guides (Mather *et al.* 2001; Harvey and Mather 2015) recommend studying the sequence at a locality on the Río Aguas, some 400m upstream of the Los Molinos to Sorbas road bridge. This locality is instructive, but suffers from two drawbacks: (1) the exposure is north-facing and thus in shade, making photography difficult and (2) the locality appears to be downstream of a wastewater treatment plant, so the locality was pervaded by a 'drains' smell and there were several pools of rather unsavoury-looking water when I visited.

The exposures at Los Molinos provide a more pleasant excursion through the gypsum-marl sequence. Los Molinos is a small village perched on the edge of the gypsum escarpment. The village is blessed with a permanent supply of water that issues from the base of the lowest gypsum unit, where it is in contact with the relatively impermeable Abad Marl. Downstream of this contact, the Río Aguas is heavily vegetated and the valley has been farmed by the villagers. The river has eroded a deep gorge through the thick lowermost gypsum units. Much of the Yesares sequence can be examined by traversing upstream through the gorge to a south-west-facing cliff cut in a bend of the Río Aguas.

Figure 12 comprises a sketch map of the Río Aguas north of Los Molinos. There is room to park several cars in a small area on the west side of the road, opposite Los Molinos village (location P on Fig. 12). Follow the track through the village down the steep valley side to the valley floor and walk north-north-west along the valley on a well-marked footpath. Here the valley is wide and heavily vegetated (Fig. 13, *opposite*).

At location A there is an interpretation board that explains the hydrogeology of the area. Beyond here the valley begins to narrow where the river has cut down through the two thick lower beds of gypsum. At location B, adjacent to an abandoned house, a large fallen block of gypsum contains some classic 'swallow tail' gypsum crystals.

The base of the lowest gypsum bed is exposed at location C, where groundwater resurgence can be observed at several places, including a channel that collects water for irrigation farther

Figure 12 Sketch map of the Río Aguas north of Los Molinos, showing the locations A to F mentioned in the itinerary. The solid line represents the minor road from the motorway junction to the town of Sorbas. Dashed lines show the course of the Río Aguas; the dot-dash line shows the route of the footpath through the village to the valley floor.

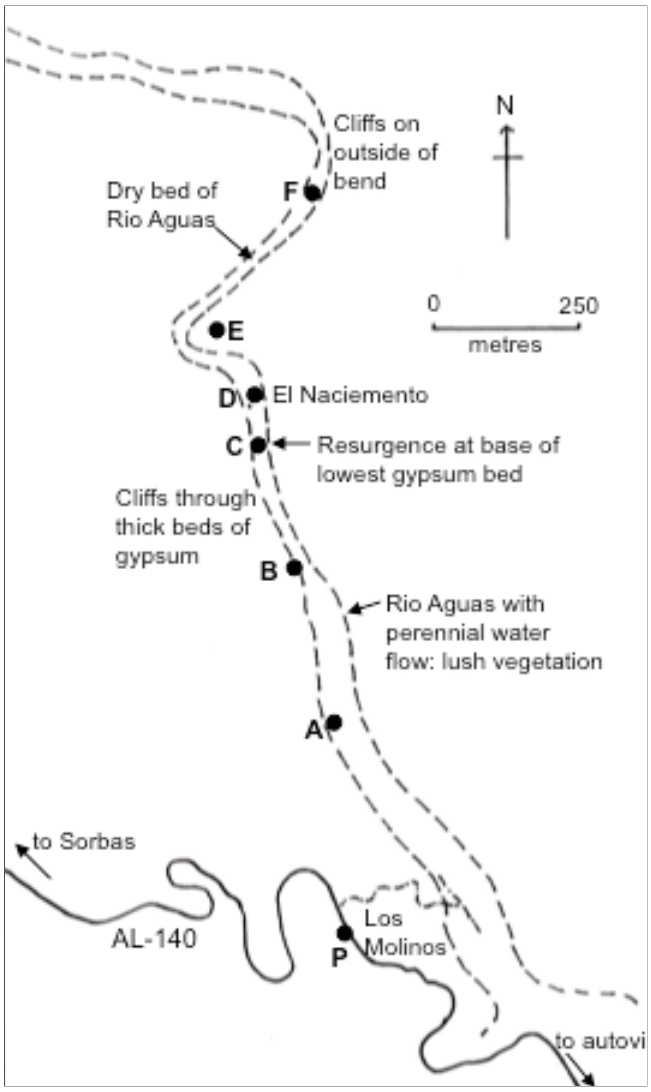
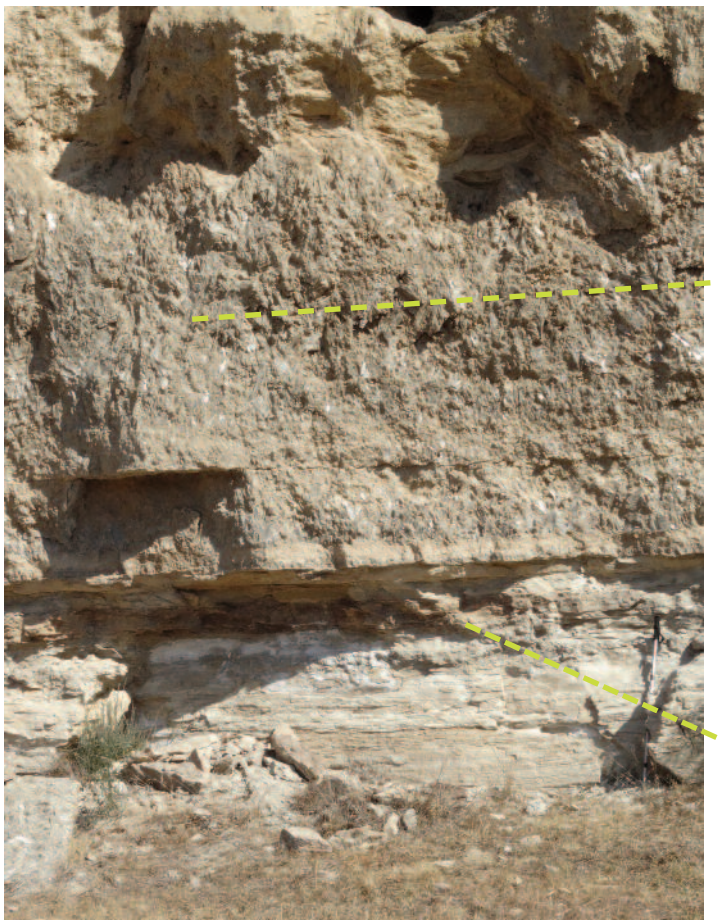


Figure 13 View north-north-west up the valley from Los Molinos. The wooded area on the RHS marks the course of the Río Aguas, which at this point has a perennial flow. On the LHS the valley narrows upstream as the river passes through a thick bed of gypsum.

downstream at the village. Above location C the river valley is dry and sparsely vegetated. At location D (El Naciemento) the valley opens out and the path cuts across a bend in the dry river bed to location E, where three gypsum beds can be seen in a north-east-facing cliff on the bend in the river.

Continue north until the dry river bed is reached, then follow it north-east to a prominent bend where four north-dipping gypsum beds are exposed on west-facing cliffs on the outside bend of the river (Fig. 14). At location F the lowest bed is well exposed at a height convenient for examination. Figures 15–17 *(overleaf)* are photographs of this bed, plus details of the large gypsum crystals and of the underlying sediments. An annotated graphic log is presented in Figure 18 *(overleaf)*. The overlying beds can be examined in turn by walking north and then north-west.

Figure 14 North-dipping beds of the Yesares gypsum exposed in cliffs on the outside of a bend in the Río Aguas, adjacent to Location F on Figure 12.



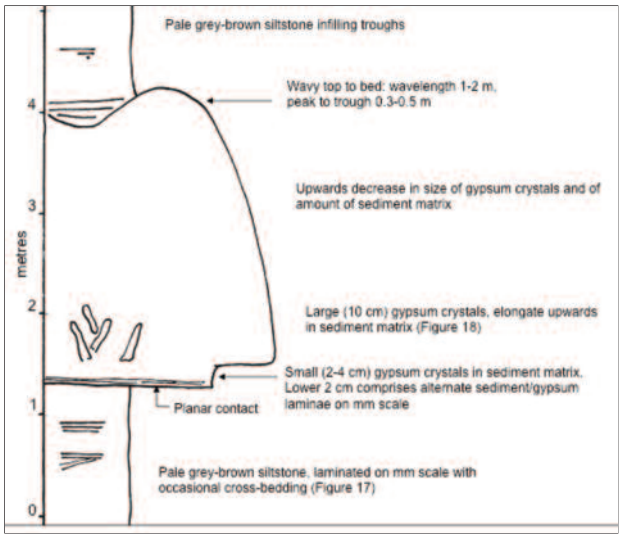

Pale grey-brown siltstone infilling troughs
Wavy top to bed: wavelength 1-2 m, peak to trough 0.3-0.5 m
Upwards decrease in size of gypsum crystals and of amount of sediment matrix
Large (10 cm) gypsum crystals, elongate upwards in sediment matrix (Figure 18)
Small (2-4 cm) gypsum crystals in sediment matrix. Lower 2 cm comprises alternate sediment/gypsum laminae on mm scale
Planar contact
Pale grey-brown siltstone, laminated on mm scale with occasional cross-bedding (Figure 17)
metres
0
1
2
3
4

Figure 15 (top left) Bed of gypsum together with the underlying and overlying sediments at location F, 37° 06.095'N 02° 04.560'W (hiking pole = 1.2m long).

Figure 16 (top right) Large gypsum crystals at the base of the gypsum bed at location F (coin = 20mm diameter).

Figure 17 (below right) Laminated siltstones below the base of the gypsum bed at location F.

Figure 18 (left) Annotated graphic log of the gypsum bed in Figure 15.

[References are opposite.]

References

Braga, J. C., Martin, J. M., Riding, R., *et al.* 2006 'Testing models for the Messinian salinity crisis: the Messinian record in Almería, SE Spain'. *Sedimentary Geology* **188–189**, 131–54

Harvey, A. M., and Mather, A. E. 2015 *Almería (Classic Geology in Europe 12)*. Edinburgh: Dunedin Academic Press

Hsü, K. J. 1983 *The Mediterranean was a Desert — a Voyage of the* Glomar Challenger. Princetown University Press

Hsü, K. J. 1987 'The desiccation of the Mediterranean sea'. *Endeavour* **NS 11**, 67–72

Hsü, K. J., Ryan, W. B. F., and Cita, M. B. 1973 'Late Miocene desiccation of the Mediterranean'. *Nature* **242**, 240–4

Hsü, K. J., Montadert, L. Bernoulli, D., Cita , M.B., *et al.* 1977 'History of the Mediterranean salinity crisis'. *Nature* **267**, 399–402

Kendall, A. C. 1992 'Evaporites', *in* Walker, R. G., and James, N. P. (eds) *Facies Models*. St John's: Geoscience Canada, 375–409

Krijgsman, W., Hilgen, F. J., Raffi, I. Sierro, F. J., and Wilson, D. S. 1999 'Chronology, causes and progression of the Mediterranean salinity crisis'. *Nature* **400**, 652–5

Krijgsman, W., Fortuin, A. R., Hilgen, F.J. and Sierro, F. J. 2001 'Astrochronology for the Messinian Sorbas Basin (SE Spain) and orbital (precessional) forcing for evaporate cyclicity'. *Sedimentary Geology* **140**, 43–60

Lunar, R., and Moreno, T. 2002 'Economic and environmental geology', *in* Gibbons, W., and Moreno, T. (eds) *Geology of Spain*. London: The Geological Society, 473–510

Mather, A. E., Martin, J. M., Harvey, A. M., and Braga, J. C. 2001 *A Field Guide to the Neogene Sedimentary Basins of the Almería Province, South East Spain (International Association of Sedimentologists Series)*. Oxford: Wiley-Blackwell

Riding, R., Braga, J. C., Martin, J. M., and Sanchez-Almazo, I. M. 1998 'Mediterranean Messinian Salinity Crisis: constraints from a coeval marginal basin, Sorbas, southeastern Spain'. *Marine Geology* **146**, 1–20

Riding, R., Braga, J. C., and Martin, J. M. 2000 'Late Miocene Mediterranean desiccation: topography and significance of the 'Salinity Crisis' erosion surface on-land in southeast Spain: Reply'. *Sedimentary Geology* **133**, 175–84

Walker, J. D., Geissman, J. W., Bowring, S. A., and Babcock, L. E. (compilers) 2012 *Geologic Time Scale v. 4.0.* Geological Society of America. **DOI: 10.1130/2012.CTS004R3C**.
http://www.geosociety.org/science/timescale/timescl.pdf
(accessed 2 May 2016)

Appendix: note on the latitude and longitude data

The latitude and longitude of each location were determined with a Garmin eTrex hand-held GPS unit, set to the WGS 84 map datum, with a minimum of six satellites in view. In all cases the error displayed was less than +/- 10m, corresponding to +/- 0.005' of latitude. The third decimal place in the minutes values recorded is thus probably not significant.

Book review

Gutierrez, Francisco, and Gutierrez, Mateo 2016 *Landforms of the Earth, an Illustrated Guide*. Springer, Switzerland (ISBN 978-3-31926-947-4; hardback, 270pp; £67.99)

This book is a photographic guide to geological and geomorphological landforms by two Spanish University lecturers, and uses more than 360 colour images from around the world, though mainly from Spain, Iceland and the USA, with a few from the UK and a number from Ireland (for glacial landforms). Their aim is to illustrate the types of landforms referred to in textbooks, but not always illustrated there, thus to aid students in visualising and understanding them. Thus there are no diagrams, just clear and well-written text and well-chosen photographs.

The pictures are magnificent, and are divided into sections; each landform or group of geomorphological features illustrated is briefly explained and then illustrated with a short caption. The structure of the book follows the classical geomorphological subdivisions, and has five chapters on structural geomorphology (structural, tectonic, volcanic, karst and granite), four on azonal geomorphic systems and processes (weathering, slope movements, fluvial and coastal), then three chapters on the three main morphoclimatic environments (glacial, periglacial, and desert and aeolian landforms. The book is rounded off with a list of further reading and an index.

To take the glacial landforms section as an example, it starts with a few pages giving a general introduction and then short, clear sections on the individual landforms; and this includes modern colour photographs of glaciers and their actions. Then follow 13 pages of photographs covering the individual landforms, the esker being an Irish example, but the drumlin photographs come from New York State, Sweden and two from Sligo, Eire. These include ground, aerial and satellite views.

The photographs are superb, and well chosen; by taking a worldwide approach the authors have been able to select the best examples for each landforms. As the authors say in their introduction, "stunning geomorphological features constitute the main features of protected areas ... and outstanding tourist attractions".

I definitely recommend this book to illustrate and understand the many types of landforms mentioned in textbooks, field guides and research papers. This is also a book to encourage us out into the field; there is a lifetime (or more) of geological fieldtrip ideas in this book.

— John Lonergan, BSc Hons (Open), FGS

Book review

Pickering, Kevin T., and Hiscott, Richard N. 2016 *Deep Marine Systems*. Oxford: Wiley and American Geophysical Union (ISBN hardback 978-1-11886-549-1; paperback 978-1-40512-578-9; 657pp; companion website www.wiley.com/go/pickering/marinesystems; hardback £9, paperback £41.59, Kindle £39.51)

The book is aimed at advanced-level undergraduates, postgraduate students and professionals. Therefore, this book will be within the capabilities of anyone who has studied third-level OU geology courses and Oceanography. It is about modern deep-sea siliclastic sediments (there is very little about carbonates), processes and depositional systems, and how they relate to the rocks we see today. The aim is to relate the structures seen in deep-sea scans and cores to those seen in outcrops of ancient marine systems.

There are three parts to the book: Part 1 Processes and product, Part 2 Systems, and Part 3 Plate tectonics and sedimentation.

There is a companion website that includes PowerPoint files of figures, PDFs and high-resolution photographs of the cores from the UCL Ainsa Project. The core photographs take a very long time to download, unless through fibre optics, although it is well worth the time because some of the detail is lost in the printing.

Part 1 considers the physical and biological processes by which sediments are transported and deposited in deep water. The dynamics of turbidities and debris flows are discussed in great detail, and there is a chapter later in the book discussing the statistical properties of sediment gravity flows. The sediments produced by the various flow types are described and organised into a facies scheme, which is then used throughout the book. The next chapter is quite a long and detailed section on ichnology; important for identifying different parts of a submarine fan deposit. The integration of time and space is an interesting chapter.

Part 2, Systems, discusses submarine fans and related depositional systems, both ancient and modern. I found this part fascinating! I never imagined that there would be whole land-delta type deposits down there. They are actually submarine fans, but they have canyons, levees, lobes and over-bank deposits that look very similar to those on land, but the sediments are transported by different mechanisms. Both ancient and modern examples are discussed in great detail.

Part 3 looks at the effects that plate tectonics have on the types of sediments deposited and on the structures of the submarine fans. Plate tectonics have a major control over the size and longevity of submarine fans, some of which are several hundred million years old and 1,000km or more long on the passive plate margins, but are short-lived and smaller on destructive plate margins.

There is no glossary, but this should not be a problem for the group for which the book is intended. The reference section is a huge 84 pages.

It is a large, heavy book that has photographs, diagrams, graphic logs, sonar scans, maps etc. on most pages and lots of examples to demonstrate the theories presented.

The above is only a very brief outline of the book's content, but I enjoyed reading this book and it will be used as a reference for many years to come, as it explains many of the structures that I see in the rocks, some of which have puzzled me for years. For the more advanced student who wishes to further their understanding of sediments this is an excellent, easy to understand reference book that concentrates on what you see in the field (or bore hole core) without overburdening the reader with formulae and statistics — highly recommended.

— Lyn Relph, BA Hons (Open,) BSc Hons (Bangor)

The Virtual Microscope for Earth Sciences: a case study at the Open University

Prof. Simon Kelley

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Introduction

The Open University has used multimedia to deliver learning 'on screen' to students since the early days of BBC TV programmes in the 1970s. Innovation in the use of media progressed through VHS recordings to CDs and DVDs as computers became part of the curriculum. Each change in multimedium brought increasing levels of on-screen and on-line interactivity. Technology-enhanced learning is now offered by the OU through numerous platforms, all aimed to enhance student experience and develop teaching beyond text and static images. In Science, Technology, Engineering and Mathematics (STEM) subjects, skills are a key educational element, which the OU helps to develop through home experiment kits and residential schools.

This report illustrates one example of OU educational technology from early digital content to on-line curriculum delivery: digital microscopy for teaching Earth Sciences and the recent development of a virtual microscope.

Background

The OU started to develop digital and virtual microscopes for several reasons. The development of virtual microscopes for biology — in particular for histology, was driven initially by telepathology (remote diagnosis using images transferred on the Internet), by issues related to use of human tissue for education (Dee *et al.* 2009; Harris *et al.* 2001; Heidiger *et al.* 2002), and because many students could view the same samples and be assessed on-line (Weinstein *et al.* 2001, 2009; Gatuma *et al.* 2014; Blake *et al.* 2003; Becerra *et al.* 2015).

The development of virtual and digital microscopes began in the 1990s with the advent of the early CCD-based digital cameras (see Harris *et al.* 2001). Cameras mounted on microscopes had long been standard teaching and research tools, but digital storage and reproduction of microscope images generally remained on paper. Use of virtual microscopy started when it became possible to rapidly store and render images on high-resolution colour screens. Use of virtual microscopes is now common, even predominant, in teaching biology and health sciences (Becerra *et al.* 2015), but are less common in Earth Science and materials science (see Tetley and Daczko 2014). One reason is because microscope study of rock thin sections requires multiple lighting conditions (plane, crossed polarisation and sometimes reflected) and rotation (to view pleochroism, birefringence colours and extinction). The aim of teaching with complex visual materials is to teach learners 'how to see' from the scientific perspective of a geologist, biologist or materials scientist (Whalley *et al.* 2011).

Health and life sciences have used virtual microscopy since the late 1990s (Harris *et al.* 2001; Heidiger *et al.* 2009). Several published studies compare the use of virtual microscopy — for its pedagogical value — with the use of physical microscopes. Some studies were undertaken during transition from teaching with physical microscope to combined use of virtual and physical (e.g. Sagol *et al.* 2015). However, these studies only record findings after the first year; there do not appear to be any long-term studies. The findings are consistent, and include studies in histology, dentistry and veterinary science (Brown *et al.* 2016; Kogan *et al.* 2014; McCready *et al.* 2013; Thomas *et al.* 2014). Staff and students were enthusiastic about using virtual microscopes, and assessment results showed that students do equally well (but not better) in recognition and identification skills using virtual microscopes. The best results come from combining virtual and physical microscopy (Becerra *et al.* 2015; Gatuma *et al.* 2014; Brown *et al.* 2016).

Teaching in Life and Health studies also progressed through video-based to CD-based systems available on campus, to BYOD (bring your own device) and outside-lab hours access, to virtual microscopes with the development of open and Internet-based systems by 2005.

The OU developed the use of digital microscopes both in Life Science and Earth Science in parallel with the development described above.

Development of the virtual microscope for OU Earth Sciences courses

The first prototype of an on-screen microscope was developed by the OU's Institute of Educational Technology in collaboration with several academics in the Department of Earth Sciences 1993. It was used to teach some of the basic concepts of geology and only available at residential schools, introduced in 1994 to meet the needs of students with disabilities who found it difficult to use conventional microscopes. The on-screen microscope improved these students' experience and was later adopted for all students. Named a 'virtual microscope', its mention in an article at the time was probably the first ever use of the term (Whalley 1995). The programme ran on a Macintosh computer and comprised a series of animations of common rock types, each rock having a pair of associated rotation points (plane polarised light and crossed polars). This key rotation imagery was achieved with 72 still photographs using a Zeiss Photomicroscope fitted with a special piece of centring wire in the camera film cassette holder. This enabled manual centring of the images after they had returned from film processing (there were few digital images at the time). Images were digitised by writing directly to Kodak Photo-CDs from the film negatives. This approach was expensive, but achieved high quality images.

One feature of virtual microscopes was quickly apparent: while a physical microscope lasts for decades, virtual microscope software and hardware is subject to the same lifespan as computer-related hardware. Thus the Portfolio Photo CD Technology and associated specialist players of early OU virtual microscope quickly became obsolete.

The OU introduced the first virtual microscope into the second level Geology course in 1999, sending it to students on a CD (by this date students were expected to have access to a PC). The CD contained 12 thin sections of common igneous and metamorphic rocks as 'hand lens' or 'virtual microscope' views, emphasising the added value of context — a feature in many later microscopes.

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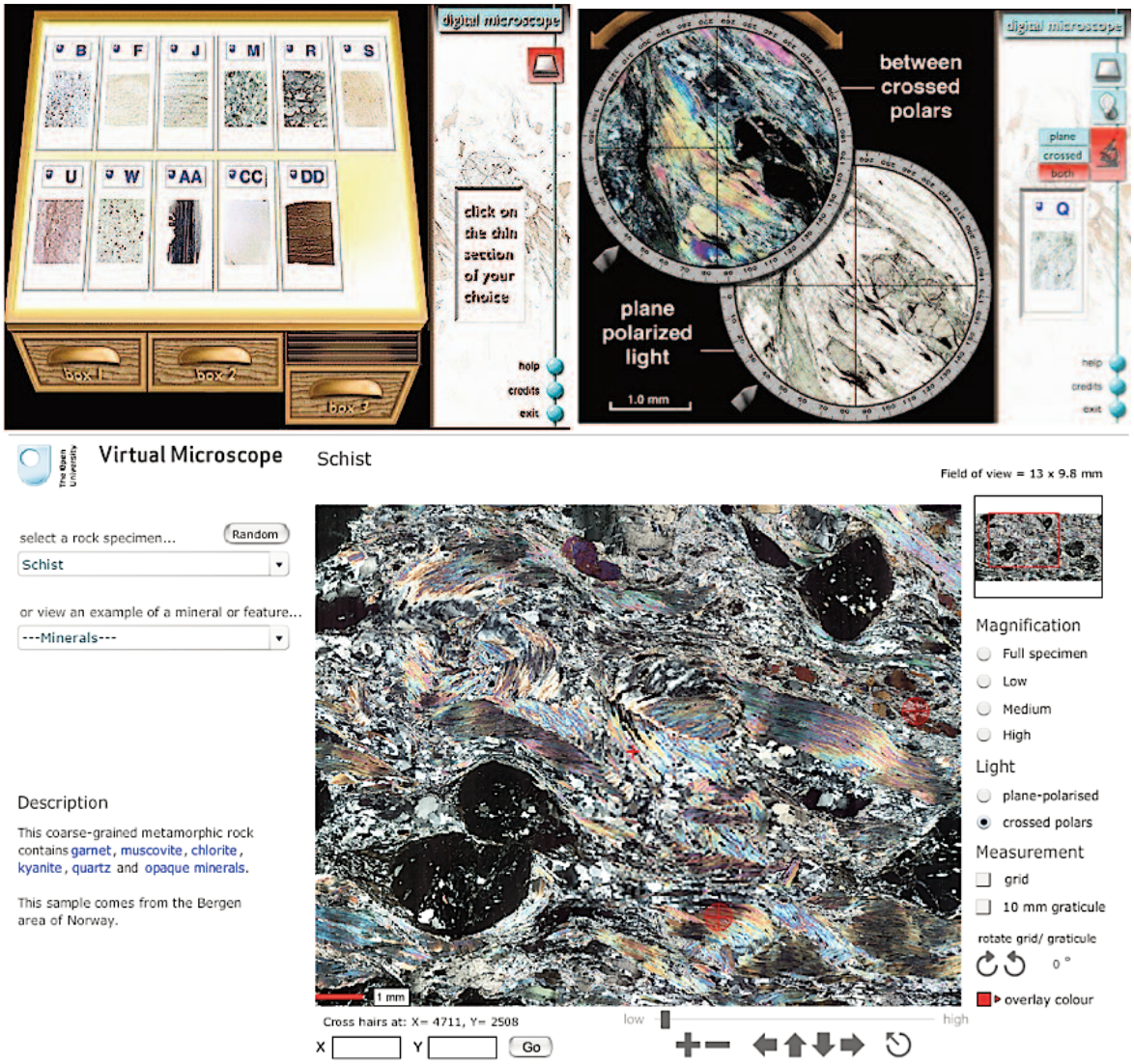


Figure 1 'Screengrabs' from the S260 digital microscope CD: top left, animated slide box, box trays 'open' to reveal virtual thin sections; top right, a thin section view simultaneously shown in plane polarised light and crossed polars; (images by Andy Tindle); bottom, 'screengrab' from the S276 virtual microscope delivered on line using Adobe Flash.

Each thin section was a single circular field of view and could be rotated in plane polarised light or between crossed polars. Trials at residential schools elicited high approval ratings from students, who found the technology easy to use. Academics and tutors also liked it because it encouraged and enabled students to make and effort to understand and deal with learning to recognise rock features and minerals without the barriers of variably maintained, or shared physical microscopes. Another key advantage proved to be homogeneity — about 800 students viewed the same thin sections; and no glass sections were broken, saving costs.

CD-based microscopes did not replace physical microscopes — these and a set of physical examples were still sent to every Geology student, for physical specimens were an essential part of the second-level course. An expanded version of the CD microscope was created for second-level Geology S260 about 1999, now called a 'Digital Microscope' rather than a virtual microscope. Multimedia were being widely introduced into OU courses and in addition to the microscope, a CD digital kit and virtual fieldtrips were added to the microscope sent to all students (Fig. 1)*.

The Digital Microscope contained 30 igneous, sedimentary and metamorphic rocks and the Digital Kit contained a visual database of 30 rocks, 20 minerals and 20 fossils. Most of the rock hand specimens could be examined in 3D rotation using QuickTime Virtual Reality software. This version of the virtual microscope won the Europrix Multimedia award in the 'Knowledge and Discovery' section in 1999, the only UK winner that year among 442 entries.

More recently, the Knowledge Media Institute (KMi) have developed prototypes of new virtual microscopes, which and have reached mainstream Earth Science teaching through Learning and Teaching Solutions (LTS) developers. Prototypes included an iPhone virtual microscope app, but memory restricted the app to three rocks. Dr Peter Whalley created the first prototype version of the new on-line virtual microscope in 2008, which ran over the Internet from a remote file server. This version used small tiled images drawn from the remote server into an Internet browser. The tiled-image system is familiar to mobile and desktop users, as it is the same as that used in most Web-based map applications (e.g. Bing maps and Google maps). This version of the virtual microscope was based on Adobe Flash software and LTS developed the application into a full student microscope for Earth Sciences and for Biology, each with a different front end (Fig. 1).

** The Editor asks for the reader's understanding: many of the figures in Prof. Kelley's article are 'screengrabs' and are therefore not of the best quality resolutions for print reproduction.*

Image panning and zooming were key advances of the new system, enabling students to explore thin sections for the first time, together with location (x and y co-ordinates), a graticule (for in-view measurements) and a grid for point counting. Text and microscope location text links enabled labelling and enhanced teaching; and finally, clicking on 'hot spots' in the image opened a new view of rotating thin section (72 images stitched into a movie). This new system did not require any software download, just a suitable browser and reasonable Internet speeds.

The system worked well, but there were issues with the speed of image transfer over some ADSL (Asymmetric digital subscriber, or 'broadband') lines — it could not be used over dial-up phone lines. While some students were able to use the system on-line, others had to use a cache system to download images into memory. OU standard at the time was 0.5MB, but some students' Internet access was slower. Therefore, the course team decided to supply the system on a high-resolution DVD, including 30 rocks bypassing the need for broadband Internet access.

This new virtual microscope based on Flash received high approval ratings from staff and students and was quickly transferred into a range of modules in the OU curriculum for Biology and Earth Sciences in 2010. However, the lifetime of the Flash-based virtual microscope was short, mainly because the first iPad tablets were released in the same year. The decision by Apple not to implement Adobe Flash on iPads sealed its fate and also that of the Flash version of the virtual microscope. However, KMi rapidly prototyped an HTML5 version of the virtual microscope and it was introduced as a Web-based system available to students the following year. The HTML5 was optimised for mobile platforms and, particularly for iPads. The new version had a simple interface that also worked through the browser on mobile phones, albeit the smaller screens made the experience less useful. Data analytics on the Open Educational Resource (OER) website have recently confirmed that much smaller numbers of users are accessing the system from mobile platforms (10–20% based on analytics on the OER site —*see below*).

Having developed the virtual microscope for OU courses, it became clear that there was external demand for Earth Science virtual microscopes. In 2012 JISC funded both the Biology and Earth Science microscopes and they subsequently formed part of the successful bid to the Wolfson Foundation for the OpenScience Laboratory, an on-line laboratory for practical science teaching. The new OpenScience Lab portal included existing OU practical science applications and added remote access to laboratory experiments and an observatory; virtual laboratories, including the virtual microscopes; virtual field investigations; and citizen science via the iSpot website.

Development of the virtual microscope as an open educational resource

JISC funding enabled the creation of an on-line Open Educational Resource (OER) collection of 100 thin sections from Igneous, sedimentary and metamorphic UK rocks. The aim was to create an on-line, freely-accessible collection as an educational resource. The project incorporated a browser-based app using the OU HTML5 software, accessible from desktop PC, laptop, tablet or mobile phone. The aim was to broaden Earth Science teaching with exemplar, rare and unique specimens of British rocks currently held in museums, university teaching collections and the British Geological Survey (BGS).

The Virtual Microscope for Earth Sciences website created using JISC funds contains several searchable rock collections that users can select from; he or she can zoom, pan and rotate specimens in variable light conditions, to develop their classification and identification skills without the need for high-cost microscopes and thin section preparation facilities. The UKVM presents a wide range of rock types, as the geology of UK includes most rock types that would be studied. It has the capacity to be reused and repurposed, as each specimen has a unique URL. Launched in 2012, Virtual Microscope for Earth Sciences is intended to engage and excite Earth Science students, and to teach mineral and rock identification skills in HE institutions and schools (Fig. 2).

The 'raw' image resources for creating a virtual microscope slide are acquired using a motorised XY stage on a Leica DM4000M microscope, generating image files of *c.* 1GB for each specimen. Rotation movies are digitised using an in-house motorised Leica DM RP microscope. The OU HTML5 software runs in a browser, using samples stored on a cloud server. The system worked well across most platforms: Windows, Mac OS, Linux, and on iOS, Windows and android tablets.

A key part of the system was the potential for location and view-sharing in emails, webpages and social media. The HTML5 software includes a 'share' button, which creates a URL containing all the details of the specimen, location, lighting and magnification. The process includes the creation of individual specimen pages, which can be reused as links in third-party websites, or as links in HE or school virtual-learning environments. Thus, the UKVM can be used in various forms, specimen by specimen.

Figure 2 A sample page from the virtual microscope for Earth Science OER site. This sample is a granite from Rockall and includes sample information, a link for the microscope slide and links to the sample location on an on-line geological map.

Figure 3 Three ways to search the UKVM collection: below, full-text based search; top right, by location; bottom right, by the age of the sample.

The website (www.virtualmicroscope.org) also includes a database searchable by name, location or rock age (Fig. 3).

Metadata underlying the rocks database includes latitude and longitude coordinates, linked to the BGS on-line UK geology maps.

Soon after its UKVM launch in November 2012 other collections were added to the site, including thin sections of moon rocks loaned by the Science and Technology Facilities Council (STFC) and The National Aeronautics and Space Administration (NASA), and thin sections of rocks collected by Charles Darwin on the voyage of the HMS *Beagle* (collaboration with the Sedgwick Museum in Cambridge).

The JISC funded UKVM project created a highly featured system, unique in virtual microscopes because it was designed to work equally well on mobiles, laptops and desktops, and included social media-sharing capabilities. Dissemination of the new system was through several routes, including public events (Fig. 4).

Involvement of the virtual microscope in the Open Science Laboratory enabled further innovation, including projects such as 'Shared Visualizations', which re-used several of the samples from the UKVM project to explore the advantages of student pairs or tutor-and-student pairs, to improve confidence and skills building using the virtual microscope when separated. A key way to build skills in a classroom is by sharing a microscope and looking at the same feature. Shared viewing with the virtual microscope was achieved using a script sent through a browser to each viewer. Movements transmitted the data to another system, and enabled switching control between the users.

A second innovation involved linking the virtual microscope with the nQuire project (http://www.nquire.org.uk/home). nQuire is an inquiry-based student learning platform that presents virtual microscope slides of moon rocks, with which the student can explore the minerals, features and textures of the rocks to help understand how they came to form the Moon's surface (Villasclaras-Ferandez *et al.* 2013).

PHANEROZOIC 0 to 542 ma
CENOZOIC 0 to 65.5 ma
QUATERNARY 0 to 2.588 ma
NEOGENE 2.588 to 23.3 ma
PALEOGENE 23.3 to 65.5 ma
MESOZOIC 65.5 to 251 ma
CRETACEOUS 65.5 to 145.5 ma
JURASSIC 145.5 to 199.6 ma
TRIASSIC 199.6 to 251 ma
PALEOZOIC 251 to 542 ma
PERMIAN 251 to 299 ma
CARBONIFEROUS 299 to 359 ma
DEVONIAN 359.2 to 416 ma
SILURIAN 416 to 443.7 ma
ORDOVICIAN 443.7 to 488.3 ma
CAMBRIAN 488.3 to 542 ma
PRECAMBRIAN 542 to 4600 ma
PROTEROZOIC 542 to 2500 ma
ARCHEAN 2500 to 4000 ma
HADEAN 4000 to 4600 ma

Figure 4.Disseminating the UKVM at a meeting in 2012 (photograph by Andy Tindle).

Partnerships arising from the OER

Perhaps the most important, but unforeseen, outcome of creating an OER virtual microscope was the number of partnerships that would arise, and how others would access and reuse the system.

Early examples

Soon after the first Adobe Flash version of the VMfES (Virtual Microscope for Earth Sciences) became available for Open University students, an alternative use was identified by Dr Neville Hollingworth of the Science and Technology Facilities Council (STFC). As part of their outreach, STFC sent small samples of Moon rock and glass thin sections to societies, schools and universities. Using STFC and OU funding, a set of 10 thin sections of Moon rocks were digitised and posted on-line. Soon afterward, two more sets of samples were digitised: one of rocks collected by Darwin during the voyage of the HMS *Beagle* (loaned by the Sedgwick Museum in Cambridge) and one a set of meteorites from the Natural History Museum London and from the Vienna Museum of Natural History, (funded by the EU project EUROPLANET), digitised and posted on-line, on the VMfES website.

University partnerships

Other partnerships arose with university departments teaching Earth Science. Teaching undergraduate mineralogy and petrology classes in conventional universities faced issues similar to those experienced in OU distance teaching. Increased access to wifi, fast Internet and personal devices, has meant that VMfES can augment mineralogy and petrology teaching in conventional universities. Conventionally, most students have access to microscopes and thin sections only during classes for a few hours per week; but digitising some of the same teaching materials gives students additional time to examine specimens. Subsequently, selected collections from Leeds, Durham and Trinity College Dublin have been digitised by Dr Andy Tindle at the OU and posted on-line, some requiring a password, others openly available (e.g. Trinity College at. These universities continued to use the VMfES over several years, often showing peaks on the same day each year, for example when Trinity College Dublin delivered its introductory petrology class (Fig. 5).

Museum partnerships — rare and inaccessible collections

Further partnerships continue to be based on these two themes — rare or inaccessible collections and collaborations to use the VMfES in university teaching. The team began to digitise all the NASA Moon rock thin sections, to make them freely available for teaching and research purposes — planning to complete this work in 2019 for the 50th anniversary of the first manned Moon landing,

The OU team worked with a consortium of Irish universities, funded by the National Forum for the Enhancement of Teaching & Learning in Higher Education in Ireland, to develop joint learning materials based on samples in their teaching collections.

A further partnership with the Natural History Museum London is to digitise all meteorites in their collection that have fallen on the UK. These are predominantlyas rotatable, 3D objects, to expand the visitor's experience outside the physical museum.

OER reuse, repurposing and remixing

An often-stated purpose of OERs is to promote reuse and remixing of materials in new contexts. The VMfES provides a range of related material, some samples having little information while others include the contexts of rock samples, descriptions of their locations, hand specimens and thin section minerals.

Reusing the VMfES

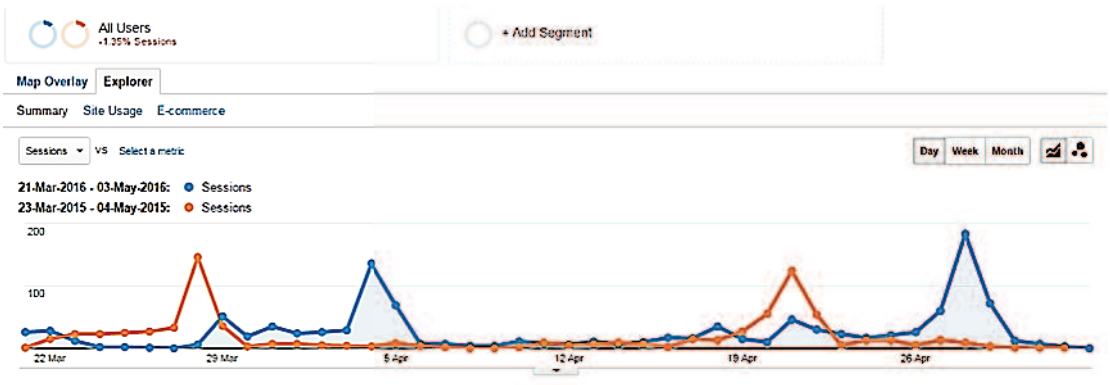
Universities are using the VMfES with numbers increasing almost linearly over its first three years as shown by the analytics on the OER site. The VMfES is becoming embedded in teaching as more academics discover the site and trust that it will remain year-on-year. An example is Trinity College, Dublin, where strong weekly peaks in use are seen in subsequent years (Fig. 5), probably during petrology classes or as deadlines for homework assessment pieces and exams approach. The use in teaching is evident in the site analytics, in the form of referrals from Institutional Virtual Learning Environments (VLE), and these indicate that teachers are creating links to particular rocks for their students year on year.

Repurposing VMfES material

Two examples of repurposing are closely related to the OU, avoiding external licensing and extra costs. The first, described above, is the link to the nQuire project.

The second was developed in 2013 specifically for the FutureLearn platform and a Massive Open Online Course (MOOC) on the subject of 'Moons'. This is a simplified virtual microscope system designed for mobile platforms, enabling learners to view four Moon rocks during two weeks of the eight-week course. The course, presented annually, attracted more than 8,000 learners in its first year.. The MOOC included several links to the OER site, shown by the visitor numbers for the weeks the MOOC was active.

Figure 5 A comparison of the numbers of sessions from the city of Dublin in 2015 and 2016. Note the two peaks of access in both years are within a week of each other.



Virtual Microscopy: Etna Basalt 21574
Below you should see the Etna Basalt thin section. Please familiarise yourself with it and the controls before we continue to some interactive exercises. If you're having trouble with the VM, you should be able to get help from the online guide to the VM which will walk you through the basic functions.
click here to progress
Virtual Microscopy: Etna Basalt 21574
The different minerals have been identified for this field of view. Note that in plane polars, the difference between olivine and plagioclase can be very subtle until you are used to relief work. On the next slide, we show XPL for comparison.
click to continue
Opaque
Plagioclase feldspar
Olivine
Clinopyroxene
Static Image - no VM this slide

Figure 6 'Screengrabs' from Dan Morgan's virtual microscope activities at the University of Leeds, using embedded microscope slides (left) with labelled views (right).

Reusing VMfES material

One example of reuse is by Dr Dan Morgan at the University of Leeds. He embedded virtual microscope thin section within the Leeds University Virtual Learning Environment (VLE) using Adobe Captive software (Fig. 6). This reuse enabled students to continue to use the microscope outside the laboratory, and for revision during re-sits in the summer.

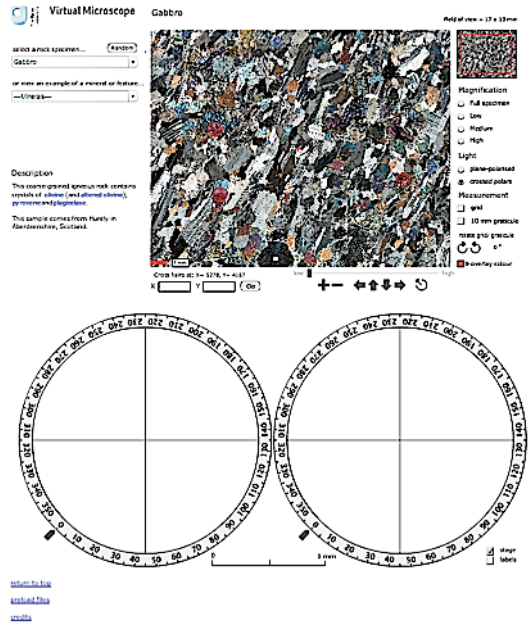
Dr Malcolm Hole at Aberdeen University implemented a more traditional, but equally effective approach. He created pdf of exercises including 'screengrabs' and links to the slides to guide students' studies. Work was completed during classes (with tutors and demonstrators) and outside classes, using the virtual microscope on their own devices.

Student experience and analytics

Students of second-level OU Geology S236 and S260 received a physical microscope in their 'home experiment kit'. The kit included a compact MacArthur microscope, later a near full-size Meiji microscope; also, a CD with the digital microscope application with simple rotating views in plane polarised and between crossed polars. The CD illustrated the same rocks as the small specimens and glass thin sections. In 2010 S276 did not include a physical microscope, only access to the on-line version (also supplied on a DVD; Fig. 7). With no simultaneous use of both microscopes by one student cohort it is difficult to assess student satisfaction and achievement of learning objectives. Student feedback was similar for both courses, and Associate Lecturers reported the new system was intuitive, with fewer student issues. Slow Internet speeds in some locations meant students relied on the DVD version rather than go on-line. Practical science teaching at Earth Science residential schools included use of physical petrological microscopes and, at some schools during 2010 and 2011, S260 students were integrated with students who had studied S276 with the virtual microscope. Tutors and staff reported S260 and S276 students were equally well prepared. It seemed that students who had used the virtual microscope were confident in what they were supposed to see, and so were able to overcome any issues with the physical microscopes. This experience mirrors the evidence reported for use of biological virtual microscopes (Becerra *et al.* 2015; Gatuma *et al.* 2014; Brown *et al.* 2016).

Outside the OU the virtual microscope was used alongside physical microscopes in direct comparison. A survey of Durham students in 2013 yielded useful insight into their attitude towards the virtual microscope. Durham students who also had

Figure 7 Transition from physical microscopes (left) sent to students as part of the second-level geology course and to the first on-line virtual microscope based on Adobe Flash ('screengrab' right).



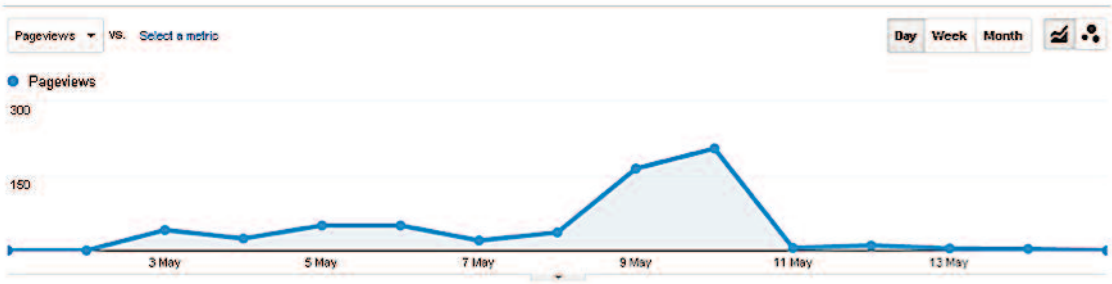


Figure 8 Durham student accessing the virtual microscope OER site during the week-long 'homework' exercise; up to 20 students used the system for the first five days, increasing to more than 150 sessions on the last two days.

access to laboratory microscopes were given an exercise to complete outside the lab. About 90 per cent of students accessed the VMfES using their own devices, and reported favourably about the quality of the images, their ability to use the built-in measurement tools, and not having to visit the laboratory to look at specimens — perhaps best summarised in one comment — "It worked". The students were also asked what they liked least, and the main issue was the restriction of rotation points — "That you can't rotate the whole slide, only certain points on it". Site analytics also monitored student behaviour over the one-week exercise (Fig. 8).

OER development over three years of activity

The virtual microscope website has been live for more than three years, monitored by Google analytics. Recorded changes in use over the three years give insight into the take-up of the OER, as there appear to be no long-term studies of OER take-up and use in the literature. The main changes and patterns are shown in Figure 9 and below:

Summary of changes in accessing the VMfES site 2013–2016

• There has been a gradual, almost linear, increase in the number of sessions: 23k sessions in 2012, 34k in 2013 and 43k in 2015.
• The proportion of sessions from UK users decreased gradually each year — 0.61 in 2012, 0.58 in 2013 and 0.51 in 2015 — as the site was used more around the world. However, the overall number of UK sessions increased: 8,824 in 2012, 12,404 in 2013 and 14,515 in 2015.
• Three cycles of OER user access are evident: daily (many users are on or close to UK time); weekly (numbers of sessions are always lowest at weekends, 2–3 times higher in mid-week); and annually (a long low-period from June to late September, and building slowly in the autumn term, a sudden low over Christmas, then high user levels in the spring term).
• The user base has been dominated by the UK, the USA, and Europe and Commonwealth countries in initial years but this is slowly changing, with notably strong increases of use in Greece, Ireland, Australia, Chile, Poland and Turkey.
• The periods of individual use give a clear indication of the type of use, with casual use yielding averages of 60 seconds or less, but peaks of use in HEIs, showing averages of 10–15 minutes.
• Peaks in use have been associated with use in HEIs, and also in popular postings on social networks such as Facebook, Twitter and Reddit. Use in HEIs have been characterised by 20–100 sessions in a day and repetitions weekly (presumably a weekly petrology lab class).
• Over the three years the proportion of returners varied from c. 25% to *c.* 40%, and tends to be lower over the summer. New users also average shorter times on the site at 2.4 minutes, whereas returners averaged 6.5 minutes.

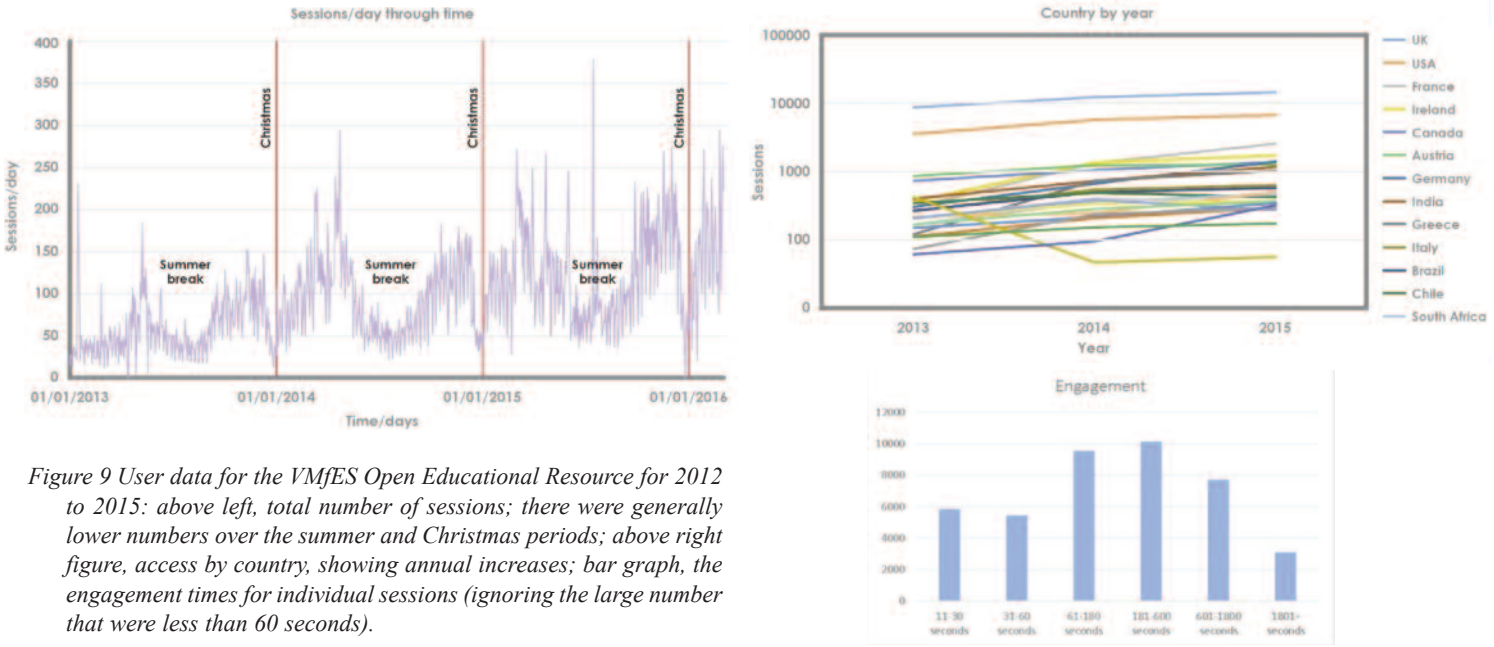


Figure 9 User data for the VMfES Open Educational Resource for 2012 to 2015: above left, total number of sessions; there were generally lower numbers over the summer and Christmas periods; above right figure, access by country, showing annual increases; bar graph, the engagement times for individual sessions (ignoring the large number that were less than 60 seconds).

• Gender data, collected since Nov 2015, indicate 57% male / 43% female users. Males spend slightly more time on site. Age is also significant, but possibly reflects overall age of Internet users — 46% 18 –24, few 65+.
• Largest number of referrals to site come through Facebook, university VLEs, museums and learned society sites.
• Most OER users access it through a desktop or laptop (82%), with fewer mobile phone (9%) or tablet (8%).

Summary and conclusions

The aim of the development of the virtual microscope, like many other OU on-line activities, was to offer a few hundred students each year a high-quality learning experience. The VMfES departed from the conventional approach when it became an outwardly focused OER and attracted external funding. Not all subsequent VMfES developments were aimed at benefiting OU modules, but the challenges thrown up by progress and inclusion of social media have benefitted OU students who have access to an impressive virtual microscope; and has developed and improved over time and at little cost to the OU. The 'Beyond Prototypes' report at http://beyondprototypes.com/ concluded that there are lessons to be learned from creating active OERs:

> *"The evidence presented in this report shows that research-led innovation in TEL is a complex process; the big successes cannot be predicted but they can be nurtured through a supportive environment that co-constructs learning and technology, supports the persistent intent of visionaries, subjects educational innovations to systematic evaluation, and partners with innovators in the education sector and in creative industries."*

Plans for further development of the VMfES include collaborative projects with a consortium of Irish universities to co-create their own learning materials, a project with NASA to digitise all available thin sections of Moon rocks, a commercial course in collaboration with a major publisher, and licensing the software for others to use independently. The aim of these projects is to sustain the infrastructure and people at the OU who continue to innovate and undertake research in Technology Enhanced Learning.

Acknowledgements

I would like to acknowledge Peter Whalley (IET and KMi), who sadly died in 2013, for the original concept of the Virtual Microscope for Earth Sciences. Andy Tindle (Science Faculty) pioneered the production of the high quality images used in the microscope and many other colleagues in Science Faculty and KMi made significant contributions.

References

Becerra, D., Grob, M., Rodriguez, A., Barker, M. J., Consiglieri, L., Ferri, G., and Sabag, N. 2015 'Academic achievement and perception of two teaching methods in histology: light microscopy and digital systems'. *Internat J Morphology* **33**, 811–16

Blake, C. A., Lavoie, H. A., and Millette, C. F. 2003 'Teaching medical histology at the University of South Carolina School of Medicine: transition to virtual slides and virtual microscopes'. *Anatom Rec* **275B**, 196–206

Brown, P. J., Fews, D., and Bell, N. J. 2016 'Teaching veterinary histopathology: a comparison of microscopy and digital slides'. *J Veterinary Med Educ* **43**, 13–20

Dee, F. R. 2009 'Virtual microscopy in pathology education'. *Human Pathology* **40**, 111 –21

Gatumu, M. K., MacMillan, F. M., Langton, P. D., Headley, P. M., and Harris, J. R. 2014 'Evaluation of usage of virtual microscopy for the study of histology in the medical, dental, and veterinary undergraduate programs of a UK university'. *Anatom Sci Educ* **7**, 389–98

Harris, T., Leaven, T., Heidger, P., Kreiter, C., Duncan, J., and Dick, F.,2001 'Comparison of a virtual microscope laboratory to a regular microscope laboratory for teaching histology'. *Anatom Rec* **265**, 10–14

Heidger, P. M., Dee, F., Consoer, D., Leaven, T., Duncan, J., and Kreiter, C. 2002 'Integrated approach to teaching and testing in histology with real and virtual imaging'. *Anatom Rec* **269**, 107–12

Kogan, L. R., Dowers, K. L., Cerda, J. R., Schoenfeld-Tacher, R. M., and Stewart, S. M. 2014 'Virtual microscopy: a useful tool for meeting evolving challenges in the veterinary medical curriculum'. *J Sci Educ Tech* **23**, 756–62

Kumar, R. K., Velan, G. M., Korell, S. O., Kandara, M., Dee, F. R., and Wakefield, D. 2004 'Virtual microscopy for learning and assessment in pathology'. *J Pathology* **204**, 613–18

McCready, Z. R., and Jham, B. C.,2013 'Dental Students' perceptions of the use of digital microscopy as part of an oral pathology curriculum'. *J Dental Educ* **77**, 1624–8

Sagol, O., Yorukoglu, K., Lebe, B., Durak, M.G., Ulukus, C., Tuna, B., Musal, B., Canda, T., and Ozer, E. 2015 'Transition to virtual microscopy in medical undergraduate pathology education: first experience of Turkey in Dokuz Eylul University Hospital'. *Turkish J Pathology* **31**, 175–80

Tetley, M. G., and Daczko, N. R. 2014 'Virtual petrographic microscope: a multi-platform education and research software tool to analyse rock thin-sections'. *Austral J Earth Sci* **61**, 631–7

Thomas, A., Ng, W., Hill, S., Rizvi, H., and Radia, D. 2014 'A virtual microscopy learning platform — a high quality, innovative and interactive tool for training haematologists of the future: a UK pilot study'. *Blood* **124**

Villasclaras-Fernandez, E., Sharples, M., Kelley, S. P., and Scanlon, E. 2013 'Supporting citizen inquiry: an investigation of Moon rock', *in* Hernández-Leo, D., Ley, T., Klamma, R., and Harrer, A. (eds) 2013 *Scaling up Learning for Sustained Impact, Lecture Notes in Computer Science*. Berlin, Heidelberg: Springer, 383–95

Weinstein, R. S., and Descour, M. R. 2001 'Telepathology overview: from concept to implementation'. *Human Pathology* **32**, 1283–99

Weinstein, R. S., Graham, A. R., Richter, L. C., Barker, G. P., Krupinski, E. A., Lopez, A. M., Erps, K. A., Bhattacharyya, A. K., Yagi, Y., and Gilbertson, J. R. '2009. Overview of telepathology, virtual microscopy, and whole slide imaging: prospects for the future'. *Human Pathology* **40**, 1057–69

Whalley, P. 1995 'Imagining with multimedia'. *Brit J Educ Technol* **26**, 190–204

Whalley, P., Kelley, S. P., and Tindle, A. 2010 'The role of the virtual microscope in distance learning'. *Open Learning: J Open Dist Learning* **26**, 127–34

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Geologically Inspired Landscape, Winner — Sally Maltby
'White Pocket Sandstone, Arizona'

Geologically Inspired Landscape, Highly Commended — Norman Nimmo-Smith
'Spider Rock Overlook, Canyon de Chelly NM, Arizona'

Geological Feature or Structure, Winner — Linda Fowler
‘Helvetic nappe folds, Tennevierge, Giffre Valley, western Alps’

Geological Feature or Structure, Highly Commended — Jenny Forrest
‘Dyke above village in the highlands of San Nicolau, Cape Verde’

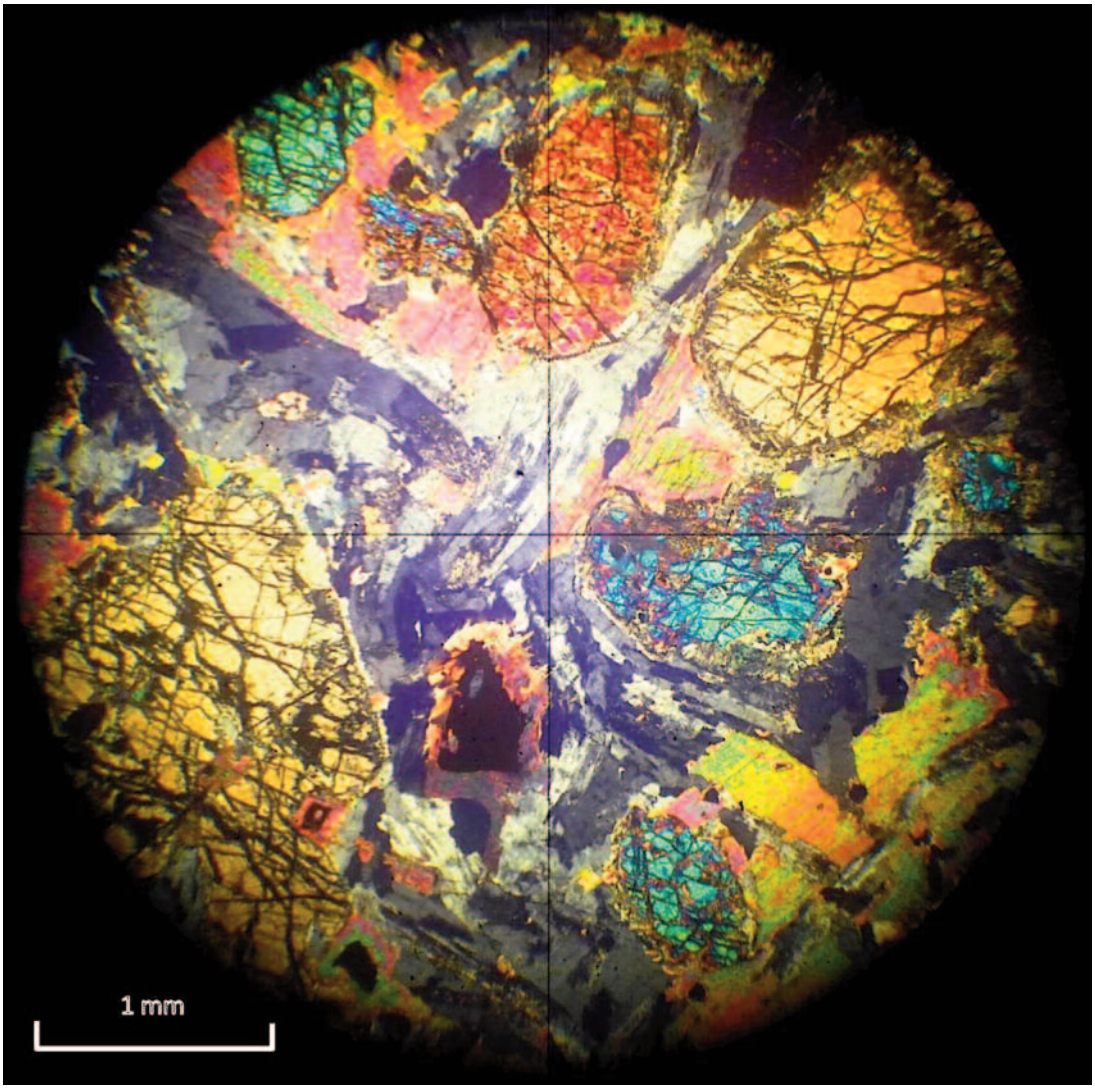
Geological Feature or Structure, Highly Commended — Ian Williamson
‘High-and-Dry, Loch Coriusk, Skye’

Geological Feature or Structure, Highly Commended — Jim Camp
‘Hopes Nose, Devon’

Industrial Geology, Winner — Jenny Forrest
'Salt pans in a crater, Sal Island, Cape Verde'

Industrial Geology, Highly Commended — Ian Clarke
'Highland Valley Copper,Logan Lake, British Columbia, Canada'

Mineral, Rock, Fossil or Slide, Winner — Linda Fowler
‘Kentallanite rock thin section, XP’



Mineral, Rock, Fossil or Slide, Highly Commended — Steve Woodward
‘Fractured calcite concretions within Dolomite Limestone, Carley Hill Quarries, Sunderland’